

**AN EXPERIMENTAL INVESTIGATION INTO ELECTROCHEMICAL
ARCMACHINING OF H. S. S.**

A Thesis Submitted
In Partial Fulfilment of the Requirements
for the Degree of
MASTER OF TECHNOLOGY

by

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to the

DEPARTMENT OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY, KANPUR
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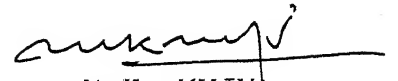
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**Dedicated
to
My Parents**

CERTIFICATE

This is to certify that the present work entitled 'AN EXPERIMENTAL INVESTIGATION INTO ELECTRO-CHEMICAL ARC MACHINING OF HSS' has been carried out by Ramachandran K.I. under my supervision and it has not been submitted elsewhere for the award of a degree.



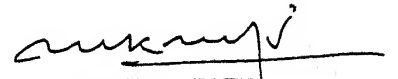
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LIST OF SYMBOLS

A	Atomic weight in grams
C	Capacitance in farads
F	Faraday's Constant (96500)
f	frequency of charging
I	Current in Amperes
K_1	Constant of Proportionality
m	mass of metal removed in grams
R	Resistance in ohms
t	Time in seconds
t^1	Charging time
U_b	Breakdown Voltage
U_s	Supply Voltage
X	Percentage weight
Z	Valency of dissolution

CHAPTER - I

INTRODUCTION

1.1 Introduction:

Electrochemical machining (ECM) and electro discharge machining (EDM) are two popular electrical machining methods. In electrochemical machining electrolytic dissolution of anode takes place causing the shape of machined part to conform to the shape of the cathode tool. The metal removal rate (MRR) is governed by Faraday's laws of electrolysis and the maximum metal removal rate is restricted by spark damage, cavitation, electrolytic boiling and difficulties in maintaining an electrolytic gap. Also an ECM plant is quite expensive.

In Electro discharge machining, metal is removed from the work piece by melting and vapourisation due to the sparks struck between the tool and the work piece in a dielectric medium. The metal removal rate is very low in EDM and achievement of high quality surface finish is difficult in the process. The sparking action causes some metallurgical damage to the work surface.

Both ECM and EDM are capable of machining complex shapes in difficult materials. ECM produces superfinish surface while in EDM accurate geometrical tolerance are possible. In EDM, MRR is low while ECM process is expensive and maximum metal removal that can be achieved is limited. Lot of research has been done to achieve high metal removal rate. High rate electrochemical machining [1] had been attempted using high voltages and high pressure flowing electrolyte.

Recently a group of research papers has appeared in a new field of electrical machining called Electrochemical arc machining (ECAM). It combines the features of ECM and EDM and the metal removal rate has been claimed to be as high as five and forty times that of ECM and EDM respectively. The process make use of larger feed rates and current density to achieve higher metal removal rate. A full wave rectified supply is used for the purpose.

It is reported that in ECAM, both electro chemical dissolution and electro discharge erosion take place simultaneously or one after the other. The electrical discharges in the form of arcs which occur between the tool and the work piece assist in the metal removal. The discharge produces craters on the work surface which are removed by electrochemical dissolution occuring randomly. The process produces good surface finish with reasonable accuracy.

In the present work, parametric study of the E C A M process has been done. The effect of voltage, feed rate concentration of electrolyte on the metal removal has been studied. Reproducibility of the corners has also been teted. Attempt has been made to throw some light on the mechanism of metal removal and the results obtained have been explained on the basis of the suggested mechanism.

1.2 Review of Literature

Electro chemical arc machining is relatively a new process. Only limited literature is available in this area. Most of the investigations had been carried out by J.A. Mc GEOUGH et al.

The first investigations into electro chemical discharge machining of conducting materials (ECAM) was done by Mamoru Kuboto and Yuji Tamura [2] in 1972. They used electrochemical discharge machining for drilling steel plates with a high feed rate of 10 - 80 mm/min. A graphite pipe electrode of 4 mm outer diameter and 1.5 mm inner diameter was used as tool and the electrolyte used was 20% NaNO_3 and NaCl solutions which is pumped through the tool at a pressure of 10 Kg/cm^2 . They found that with increase in feed rate surface roughness increases (Fig. 1.1). At lower feed rates surface finish is similar to ECM and at higher feed rates surface finish deteriorates. They also found that with NaNO_3 solution the surface was covered with a dark film. The hole shape accuracy in the case of NaNO_3 was found better than that of NaCl . The electrode wear was found to be a function of feed rate (Fig. 1.2)

In 1981, T.H. Drake and J.A. Mc Geough [3] carried some experiments in drilling by ECAM. The tool was kept stationary and the work piece vibrating with a constant amplitude was given a constant feed. They investigated the

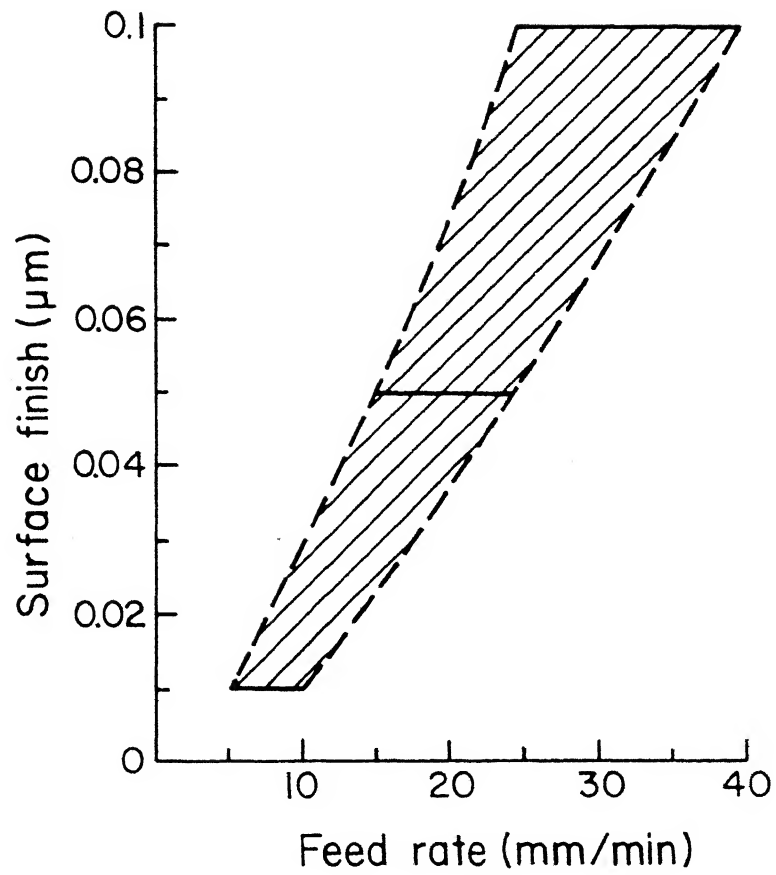


Fig.1.1 Variation of surface finish with feed rate [2]

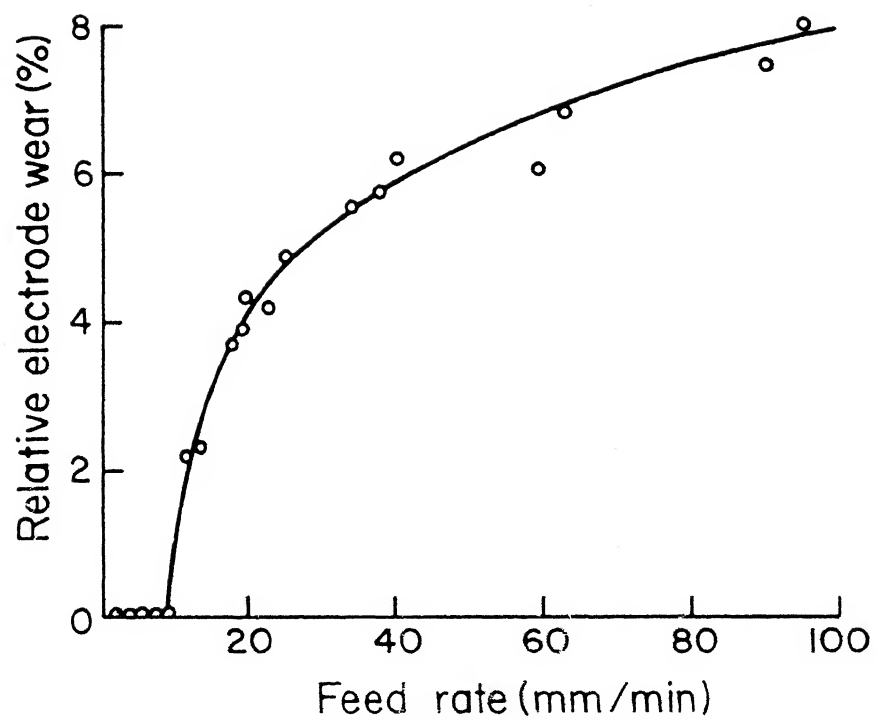


Fig.1.2 Effect of feed rate on relative electrode wear in end length [2]

effects of voltage, feed rate, phase angle and amplitude of vibration on M.R.R. and electrode wear rate. They also studied the geometrical conditions and metallurgical effects of the work piece. With change in phase angle from lag to lead, M.R.R. was found to increase initially and then decreases. With increase in amplitude, M.R.R. and tool wear rate is found to increase. Increased amplitude causes more sparking on sideways and leading edge of electrode. At lower feed rates M.R.R. was found to be lower while at higher feed rates M.R.R. was found higher. At higher feed rates the interelectrode gap was less giving rise to increased current density and sparking. The wear rate was also found increasing with feed rate. The M.R.R. and tool wear rate was found to increase with voltage due to higher ECM rate and increased energy content of sparking.

The intensity of sparking and its long time duration were considered to be the main contributing factors in enhanced metal removal. Like in EDM the spark was found to cause metallurgical damage to the work piece which could be removed by ECM phase to some extent. Typical depth of damaged layers at the inlet and outlet of drilled hole were 0.015 and 0.15 mm respectively. The depth of damaged layer was found to increase with voltage and feed rate. The study of the geometry of the drilled holes showed that the amount of taper increases with feed rate and voltage (Fig. 1.3, Fig. 1.4)

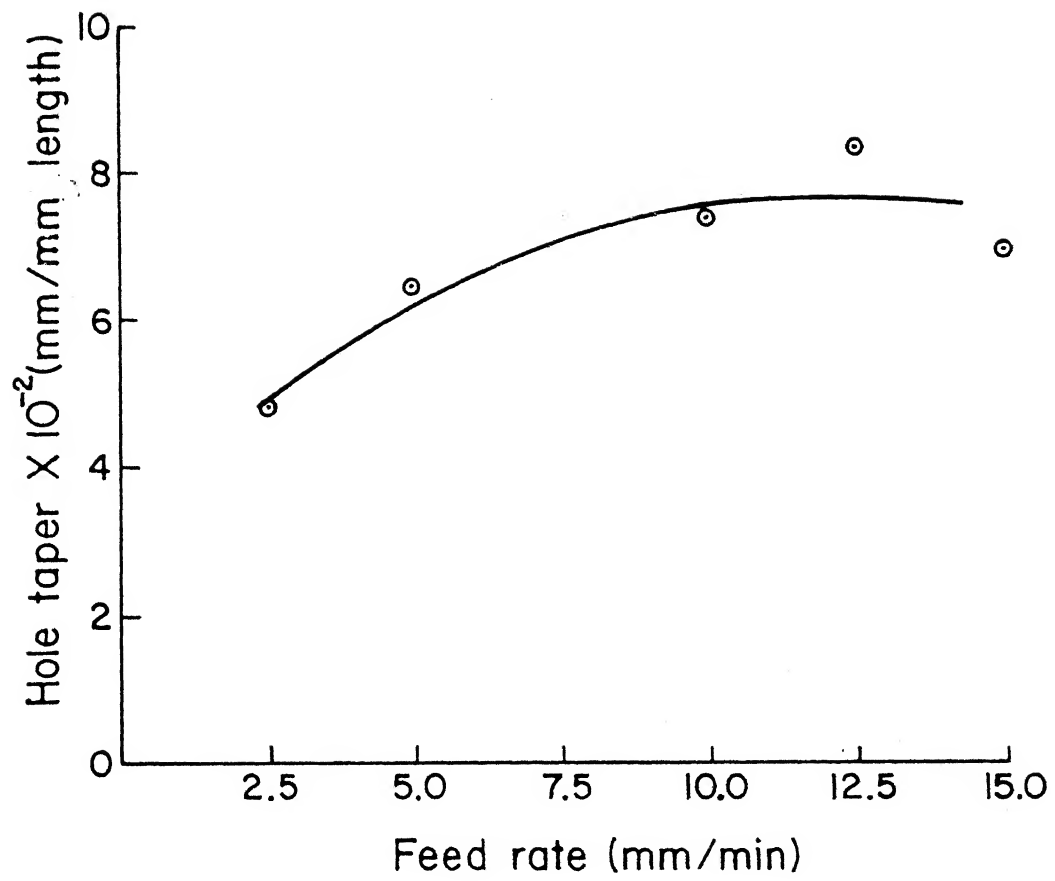


Fig 1.3 Effect of feed rate on taper of drilled hole [3]

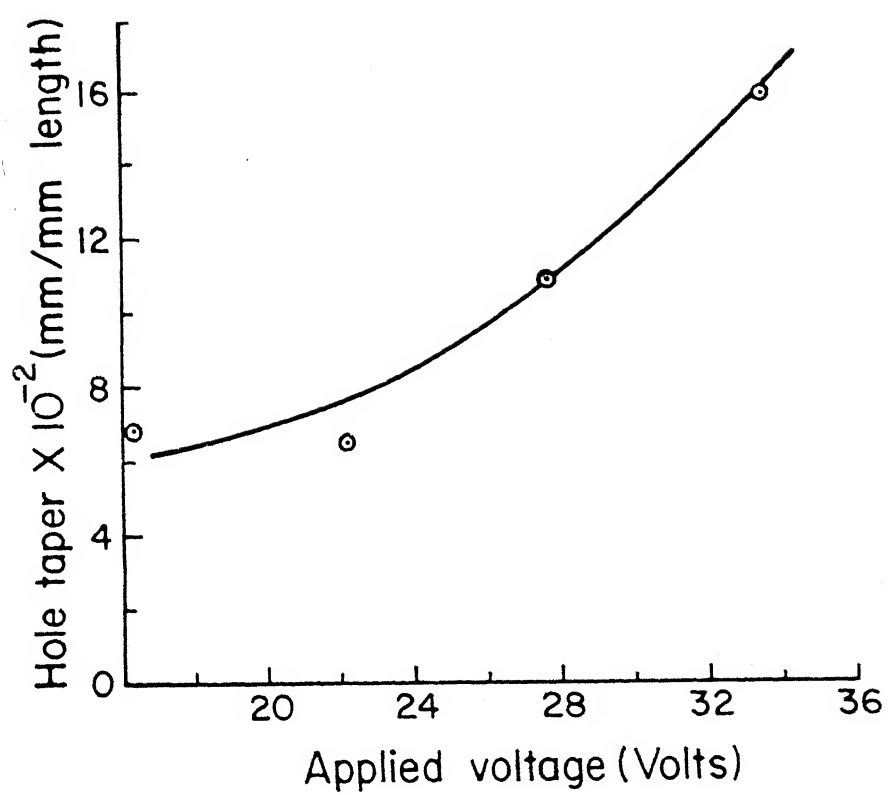


Fig 1.4 Effect of applied voltage on hole taper [3]

In 1983 I.M. Critchen and J.A. McGeough [4] investigated the discharge mechanism in Electrochemical Arc Machining. According to them, two types of discharges may occur in an electrolyte - spark and Arc discharges. Spark discharge occurs between the tool and the electrolyte through bubble formation irrespective of the gap. Arc discharges occur when spark discharges grow to bridge the gap between tool and work piece. It was found that spark discharge has little influence on M.R.R. while arc discharges produce craters on the metal surface. Previously it was found by Larson and Baxter [9] that the rate of sparking between tool and work piece increases with feed rate and decreases with increase in voltage. Critchen and McGeough studied the type of discharge by means of a square wave pulse of 200 μ s duration and separated out the EDM and ECM at different gaps. They found that discharges occur at gaps ranging from 10 μ m to 90 μ m. For NaCl electrolyte EDM phase was found to predominate for all gaps and for NaNO_3 solution, EDM action was found predominating up to 55 μ m and after that ECM action was found to have more influence (Fig. 1.5).

In 1983, J.A. McGeough, A.B. Khayry and W. Munro [5] investigated the relative effect of spark erosion and electrochemical dissolution by theoretical means. They analysed conditions favourable to ECM and arcing. They modelled the ECM component of ECAM and predicted the effects of feed

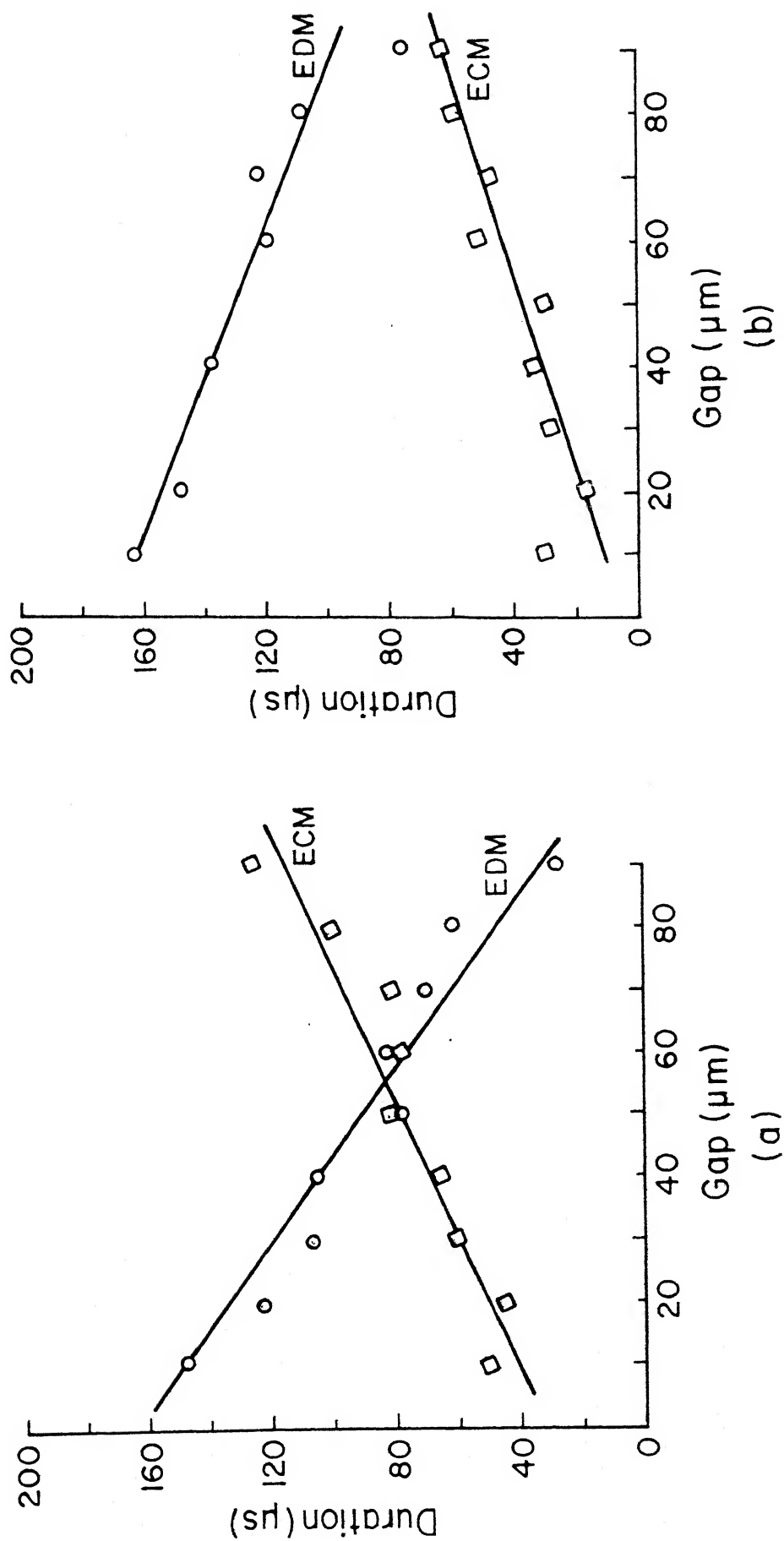


Fig 1.5 Variation of ECM and EDM phases with gap during 200μs pulse
 (a) 3M NaNO₃ electrolyte (b) 3M NaCl electrolyte [4]

rate and voltage on M.R.R. and compared the results with experimental results (Fig. 1.6, Fig. 1.7).

In 1985 A.B. Khayry and J.A. McGeough modelled the ECAM process by dynamic data system[6]. The random occurrence of spikes in the working voltage and machining power that arise during the electro chemical dissolution phase and discharge erosion phase was described in terms of stochastic difference equations obtained from D.D.S. modelling method. The spectral moments of the voltage and power profiles developed from these models were used to differentiate between the two phases as well as the occurrence of arcs and sparks in discharge erosion phase. From their investigations it was found that applied voltage in ECAM has more influence on machining followed by the phase angle and feed rates. Fig.1.8 shows the effect of voltage on linear metal removal rate and tool wear at feed rates of 10 and 25 mm/min Fig. 1.9 shows the contribution of electro discharge erosion and electro chemical dissolution phases at different voltages.

In 1986, A. Deselva and J.A. McGeough [7] studied the surface effects of alloys drilled by ECAM. They used different alloys - low carbon chrome steel, cobalt alloy, nickel alloy, low alloy steel and titanium. They made longitudinal sections of the drilled hole and took photomicrographs at different regions - near entry, middle and near exit. In the

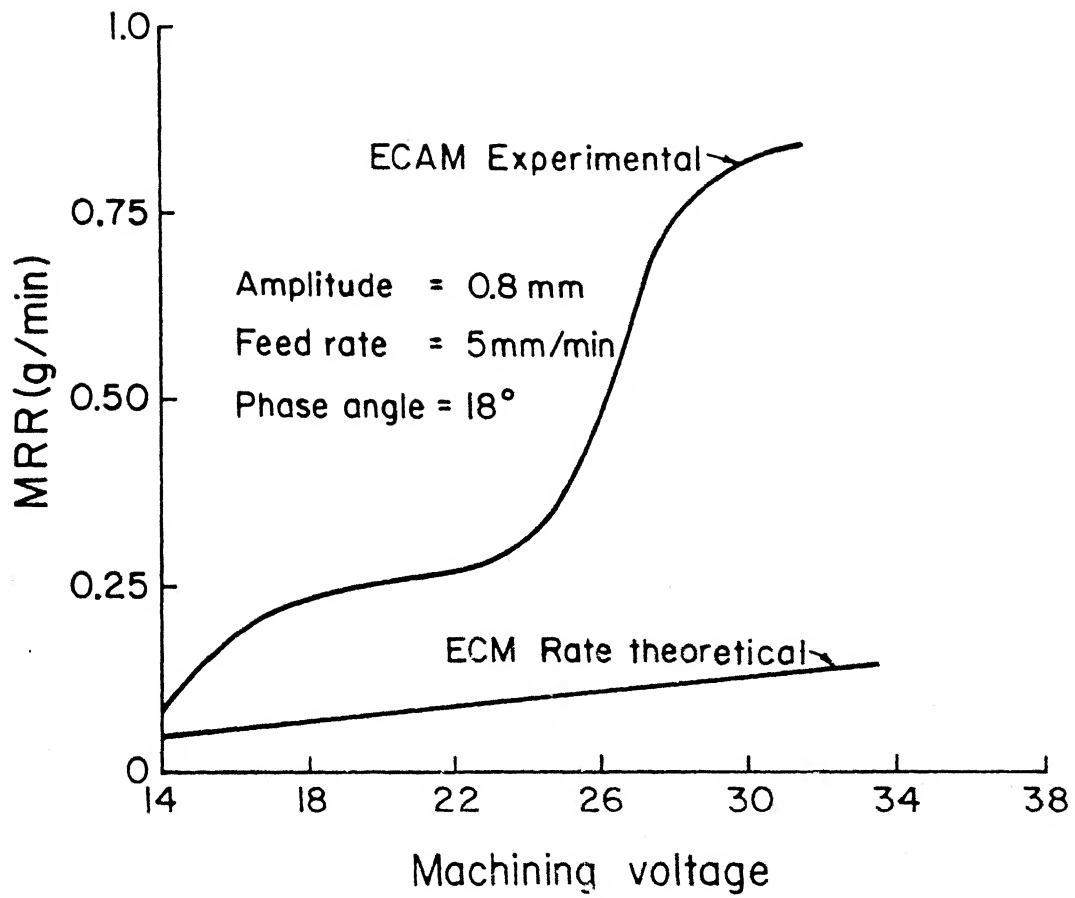


Fig.1.6 Effect of machining voltage on metal removal rate [5]

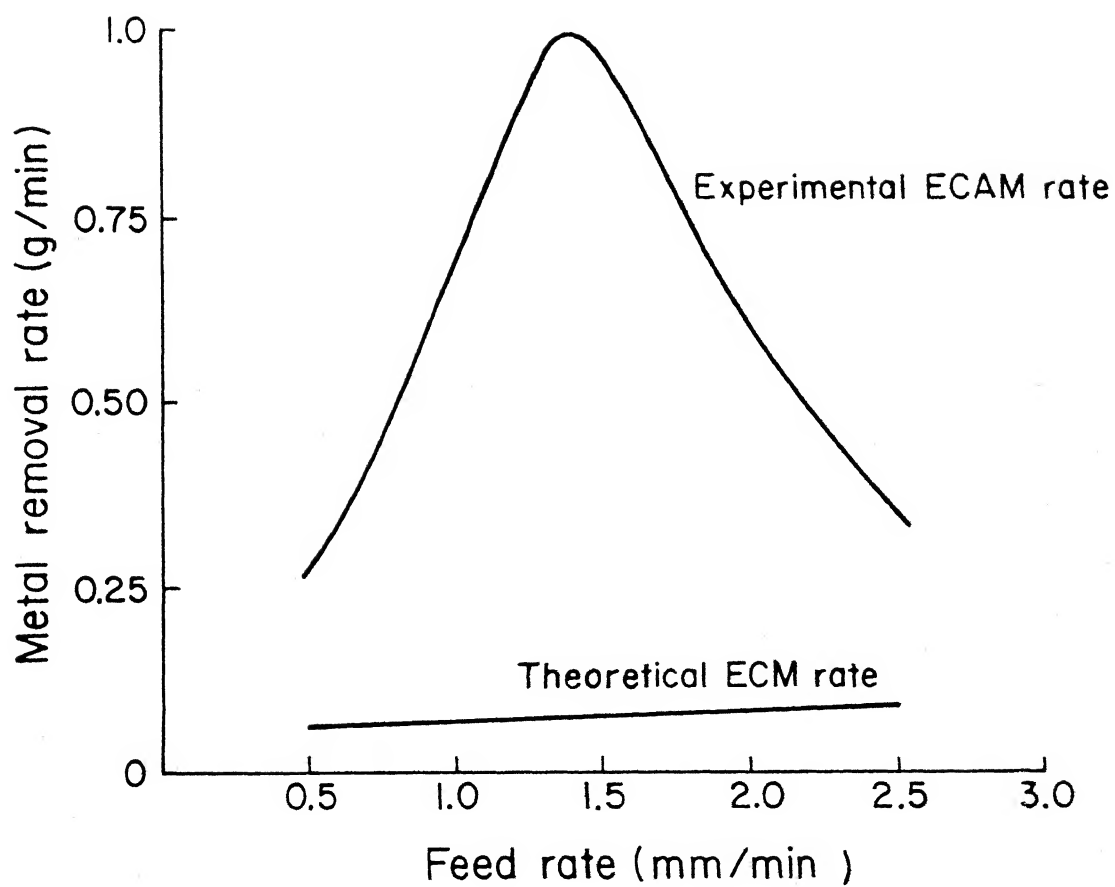


Fig.1.7 Effect of feed rate on MRR [5]

entry there was rounding off effects due to stray ECM action. In the middle combined ECM and discharge erosion was found to occur and in the exit only discharge erosion phase was found to occur. Generally it was observed that in the entry and the middle there is no surface damage while in the exit region some surface damage was observed which was explained as due to the lack of electrochemical dissolution. Alloy alloys except titanium exhibited good surface finish. Titanium exhibited poor surface with severe micro-cracking due to the formation of tenacious oxide film.

In 1987, A.N. Khayry and J.A. McGeough [8] analysed electrochemical arc machining by stochastic and experimental methods. The spikes in voltage and power profiles were analysed to describe the electrochemical and electrodischarge erosion phases. The strategy they adopted was to divide cutting region into three. In the first region between the leading edge of tool and the anode surface, metal is removed by thermal erosion. In the second region the transition from front gap to side gap where gap is larger both dissolution and discharge erosion take place. In the third region similar to side gap, the machining was considered to be sustained by electrochemical dissolution. They considered the mechanism to be a combined effect of electro chemical dissolution and electrodischarge erosion. The discharge occurs due to high electric field occurring in

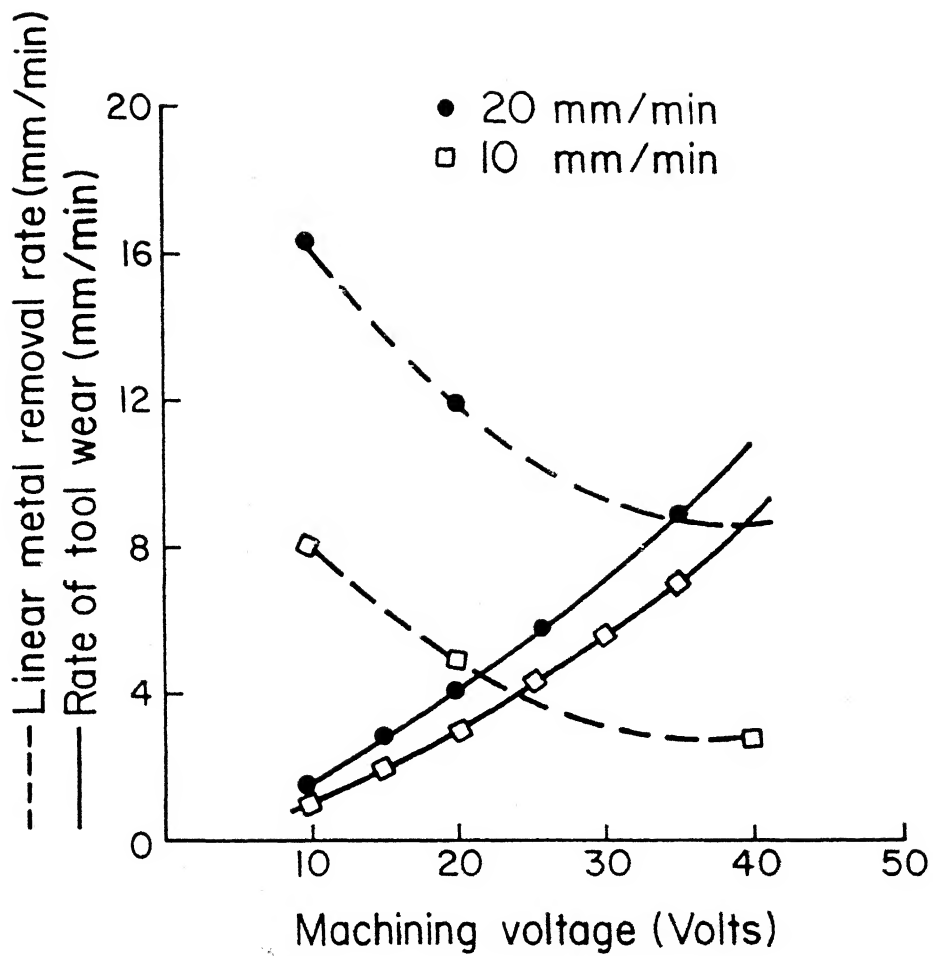


Fig.1.8 Variation in linear metal removal rate and rate of tool wear with machining voltage at different feed rates [6]

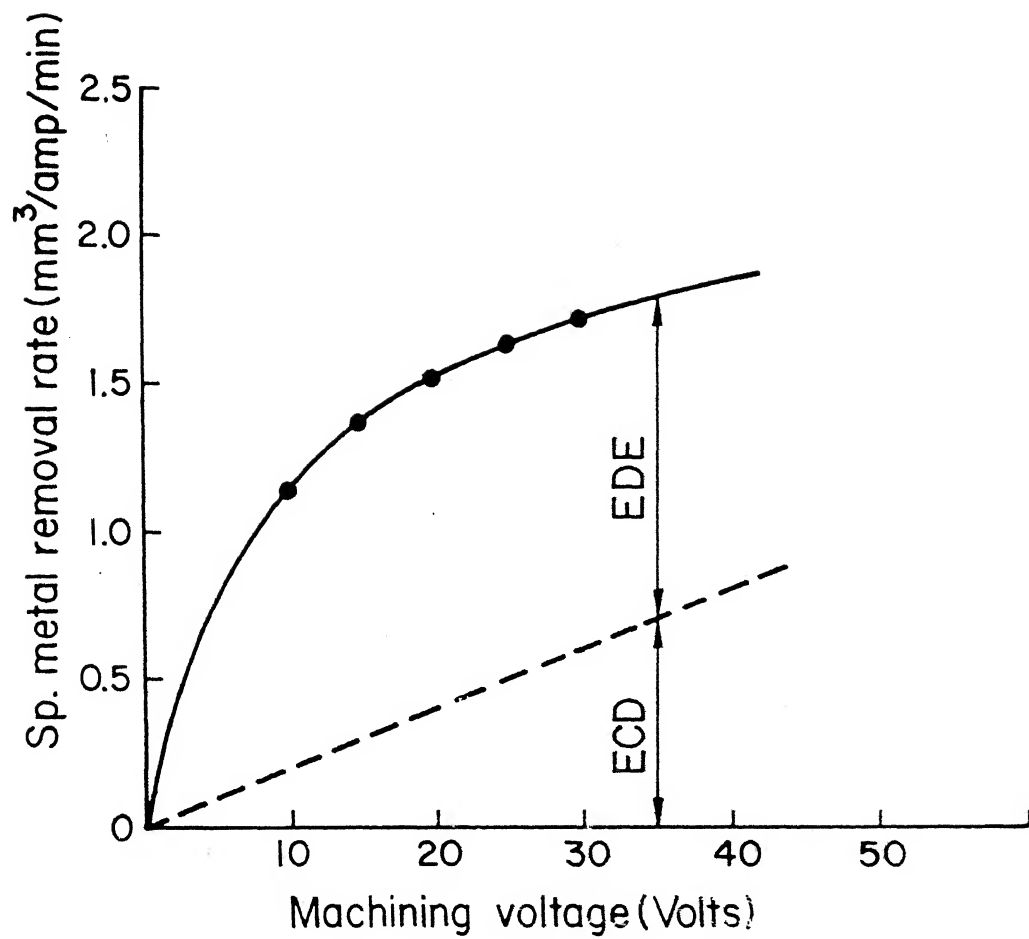


Fig.1.9 Variation in specific metal removal rate with voltage for ECM and ECAM [6]

the small gap due to which there is emission of avalanche of electrons. The avalanche of electrons melts and vapourises the metal. This is followed by dissolution phase.

1.3 Objective and scope of present work

Electro chemical Arc machining (ECAM) is a new process which involves a combined effect of electro chemical dissolution and electro discharge erosion resulting in very high metal removal rate. Only limited literature is available and the mechanism of metal removal is not yet clear.

The present work has been taken upto investigate the possible application of ECAM to the machining of hard and difficult materials like H.S.S. The entire work, however is confined to machining of H.S.S., as this is a very important tool material and no results are available for this material. The effect of voltage, feed rate, concentration of electrolyte etc on M.R.R. has been studied. A possible mechanism of metal removal has been suggested.

An attempt was made to detect the existance of arcs and sparks inelectrolyte by radio signal technique [10] . During sparking high frequency radio signals above 1 MHz are emitted and during arcing the frequency level is below 0.5 MHz. An electronic circuit was designed and fabricated to detect the arcs and sparks. But due to high level noise problem this objective couldn't be realised within the limited time available . Further modification of the circuit was necessary.

In the present work, the MRR obtained is 2 - 3 times that of ECM. The process can be advantageously used for rough machining difficult alloys like H.SS. The present work can further be extended to machining difficult materials like titanium, tungsten carbide and hard alloys

CHAPTER - II

MECHANICS OF ELECTRICAL MACHINING PROCESSES

2.1 Electrochemical machining

Electrochemical machining was developed out of the evergrowing demand for a machining process capable of dealing economically with increasingly difficult-to-machine alloys. It was adopted later as a suitable method for machining curved surfaces of complex gas turbine blades.

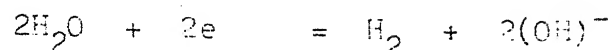
The basic phenomenon of electrochemical machining is electrolysis. When an electric current is passed between two electrodes dipped in an electrically conducting solution, some chemical reactions occur. For example in the case of two copper electrodes dipped in copper sulphate solution, the positively charged copper ions move towards cathode and get neutralised by negative electrons. The metal from the anode dissolves into electrolyte as positively charged ions so that the electrolyte in the bulk remains neutral. The net effect is dissolution of metal from anode and deposition of metal on the cathode. Electroplating and electropolishing are applications of electrolysis.

Electrochemical machining is a special type of electrolysis where there is only anodic dissolution and no deposition on the cathode. To explain it, consider the electrolysis of iron in sodium chloride solution. When a potential difference is applied between anode (Fe) and cathode

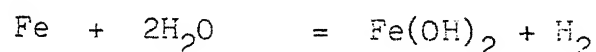
the possible reactions that can occur are:



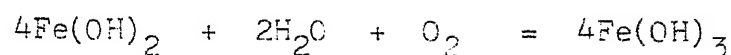
At the cathode, hydrogen gas and hydroxyl ions are produced



the metal ions combine with hydroxyl ions to produce metal hydroxide. The net reaction is;



Ferrous hydroxide may further react with oxygen and water to form ferric hydroxide



Thus electrolysis involves only dissolution of iron from the anode and generation of H_2 at the cathode. Thus in electrochemical machining only dissolution of anode takes place, the dissolution rate obeying Faraday's laws of electrolysis. The dissolution rate is not affected by the mechanical properties of metal like hardness. Only hydrogen is evolved at cathode and the shape of the cathode remains the same. This is one of the most important factors for ECM to be used as a metal shaping process.

Figure 2.1 shows the basic working principle of ECM. The metal to be machined is used as anode and tool is used as cathode. For complicated shapes to be machined, a complementary shape is produced as the cathode tool. A voltage

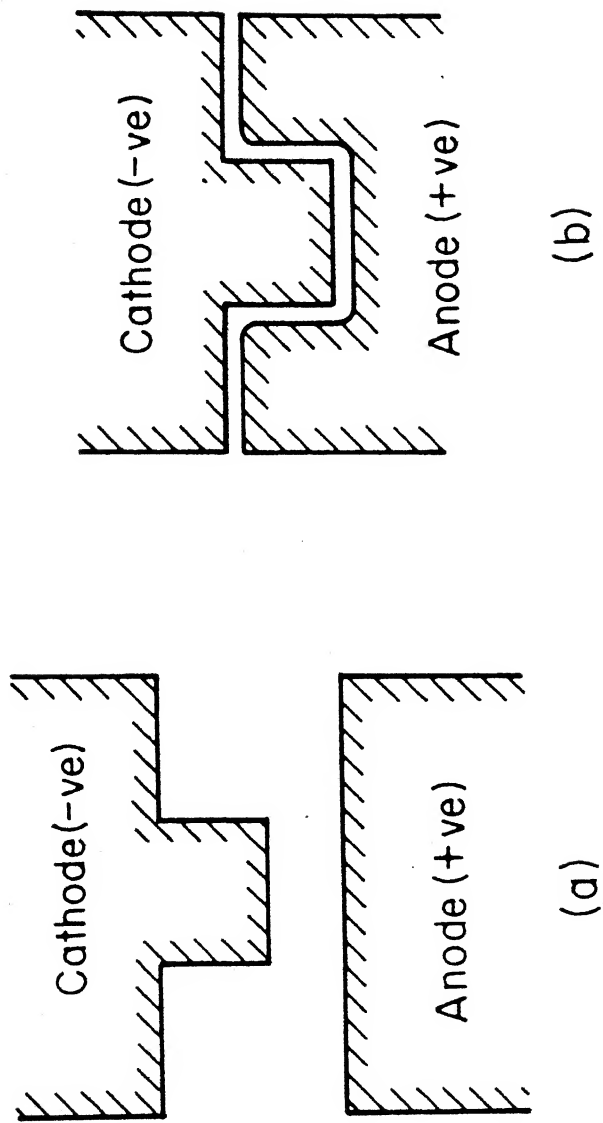


Fig.2.1 ECM Configuration(a) Initial configuration
(b) Final configuration

ranging from 3 - 20V is applied. The electrolyte (eg : aqueous NaCl) is pumped at a rate of 3 - 30 m/sec. through the gap to remove the products of machining. The initial gap is maintained to be about 0.4 mm and average current density is of the order of 50 - 150 A/cm². The metal removal rate is inversely proportional to the gap. The tool is fed at a constant rate which depends upon the current density used. The gap will gradually tend to a steady state value. Under these conditions a shape complementary to the shape of cathode will be produced on the work surface. The basic electrolytes used in ECM are NaCl, NaNO₃, KCl, NaClO₃ etc.

According to Faraday's laws of electrolysis the amount of metal removed (dissolved) is directly proportional to the amount of electricity and the amounts of different substances dissolved by the same quantity of electricity are proportional to their chemical equivalent weights. The laws can be put in the form of equation as

$$m = \frac{A I t}{Z F} \text{ ----- (1)}$$

Where

m = mass of metal dissolved

A = atomic weight,

I = Current passed in Amp.

t = the time in secs

Z = Valency of dissolution and

F = Faraday's constant = 96500

Based on this, the metal removal rate in ECM can be found out.

2.2 Electrodischarge machining (EDM)

The erosive effect of electrical discharge was first detected by Preistly, an English Scientist. Later Soviet scientists Lazaranko and Lazaranko made use of the destructive effect of electrical discharges and developed a controlled method of machining. In 1943, first spark erosion machine was constructed and in later years improvements were made in the power supply circuitry.

EDM involves controlled erosion of electrically conducting materials by initiation of rapid and repetitive electrical spark discharges between the tool (cathode) and workpiece (anode) separated by a dielectric medium. A suitable gap is maintained between the tool and workpiece. When a sufficient voltage gradient is set up between the tool and the workpiece, breakdown of the dielectric medium takes place due to strong electrostatic field between the electrodes. As a result there will be a cold emission of electrons originating from the micro irregularities or small protrusions on the electrode surface (Fig. 2.2) having shortest path in between them. Thus a free electron emitted from the cathode surface gets accelerated towards the anode attaining high velocity. It collides with dielectric molecules breaking it into ions and free electrons.

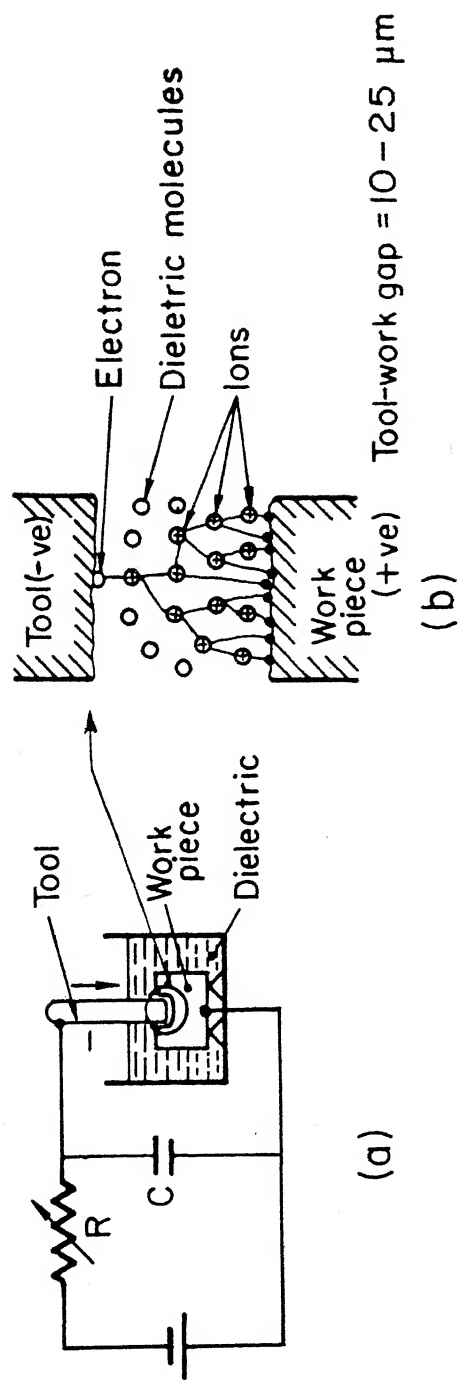


Fig. 2.2 Electrodischarge machining

(a) Basic configuration (b) Dielectric breakdown

The process continues and an avalanche of electrons are generated moving towards the anode. The path thus become ionised and fully conductive for the discharge to occur. Each electrical discharge causes a focussed stream of electrons to move with a high velocity and acceleration from the cathode towards the anode surface. This creates compression shock waves on both electrode surfaces, the pressure created being much higher than the ultimate strength of electrodes. The compression shock waves produce local rise in temperature. The phenomenon is accomplished in few minutes and the temperature of the spot hit by the electrons rise upto $10,000^{\circ}\text{C}$. At this temperature the electrode surface melts and evaporates. The metallic vapours are quenched by surrounding fluid taking the shape of small spherical globules leaving craters in anode and cathode surface. With termination of electrical conduction, the ionised column collapses and surrounding fluid occupies the place. The cathode wear is less than the anode wear due to the following reasons.

- (1) The sparks create a compressive force on the cathode
- (2) The momentum with which the ions strike the cathode is less than the momentum with which the electrons strike the anode.

Fig. 2.2 shows the working principle of EDM using a relaxation circuit. The circuit comprises a D.C. power that charges a capacitor across a resistance R . The condenser

is initially uncharged and when DC supply is switched on, a heavy current flows in the circuit with condensor voltage raising continuously. When the condensor voltage equals the breakdown voltage of the gap, discharge occurs. After the discharge, the dielectric deionises, capacitor is recharged and the cycle repeats. In practice the gap is so adjusted that the breakdown occurs when gap voltage is equal to 0.72 times the supply voltage. Working gap is of the order of 0.025 - 0.05 mm. Forced circulations of dielectric is needed to flush the gap. An automatic feed back control is used withdraw the tool when arcing or short circuit occurs.

The MRR is proportional to the frequency and the energy per spark.

$$\text{MRR} = K_1 f \left(\frac{1}{2} C U_b^2 \right) \text{-----} (2)$$

Where

U_b = the breakdown voltage.

K_1 = proportionality constant

$f = \frac{1}{t'}$ Where

$t' = RC \log_e \left(\frac{1}{1 - U_b/U_s} \right)$

$$\therefore \text{MRR} = \frac{K_1}{2R} U_b^2 \left(\frac{1}{\log \frac{1}{1 - U_b/U_s}} \right)$$

2.3 Process parameters - Capabilities and limitation of ECM & EDM:

Electrochemical machining:

Electrochemical machining can be used for machining all metals, alloys and materials which are good conductors of electricity. The machining is not influenced by hardness, toughness & brittleness of the material to be machined. It is widely used for machining of high strength, heat resistant alloys used in aircraft industries. Typical applications are the machining of turbine blades, thinning of trailing edges of airfoil blades sectioning of tough alloys bars and billets etc. It is also used in machining complex three dimensional surfaces, profiling any odd shape countours, deburring, grinding honing, diesinking etc.

The propeties which makes this process so widely applicable are stress and burrfree machining and no tool wear. The metal removal rate in ECM is higher especially when harder materials are being cut. Machining of complicated shapes may be many times faster than conventional machining of soft steel. The surface finish is of the order of 0.2 to 0.8 microns (CLA) depending on the work material and electrolyte. Dimensional accuracy is also satisfactory in ECM.

The main drawback of ECM is the high energy consumption (150 times that required for turning or milling of steel). Also equipment required is very expensive.

Material removal rate in ECM is governed by faraday's laws of electrolysis and is given by the equation (1). In practice not all of the current is used in dissolving the metal from the anode and the actual rate of metal removal depends upon the current efficiency - the proportion of total current that is used in removing metal from the anode. In practice metal removal rates of from 75% to 100% theoretical rates are achieved. Theoretical rate depends upon the current density and chemical composition of the workpiece. With increase in current density, metal removal rate increases. The metal removal rate is of the order of $8 - 16 \text{ cm}^3 \text{ mm}^{-1}$ per 10,000 Amp. The rate at which the tool is fed depends upon the current density used. The feed rate may be as great as 0.5 - 1 cm/mm, but is more usually about 1 mm/min.

The surface finish produced by electrochemical machining is usually in the range of 0.1 - 1 microns. The surface produced has better wear, friction and corrosion resistance. If the electrolyte- work piece combinations or operating conditions are not correct non-uniform dissolution of metals and alloys occur leading to selective etching, intergranular attack and pitting. This can be avoided by proper heat treatment of alloys aimed at proper dissolution characteristics. Unlike conventional finishing, ECM produces a stress free surface. It gently removes the surface layer. ECM

generally does not affect the mechanical properties such as fatigue strength. But with some metals there is an improvement or degradation of mechanical properties. For example, in the case of berryluim and tungsten ECM produces a marked improvement in mechanical properties.

Electrodischarge machining:

Electrodischarge machining finds wide application in the machining of dies (diesinking), tools made of tungsten carbide, stellites or hardsteels. Alloys used in aircraft industry like hastalloy, nimonic etc can also be machined conveniently by this process. It can also be applied for blind complex cavities, microholes for nozzles, non circular holes, narrow slots etc. The major drawback of the process is high specific energy consumption (50 times the conventional processes). The material removal rate is rather low. The surface tends to be rough for larger material removal.

The mechanism of metal removal in EDM being the thermal erosion due to spark, both work and tool surface gets eroded. The ratio of metal removal rate to tool wear rate ranges between 0.1 - 10. The maximum metal removal rate that can be achieved is $5 \times 10^3 \text{ mm}^3/\text{min}$ and the specific power consumption is $1.8 \text{ w/mm}^3/\text{min}$. In an R-C circuit the MRR is given by the equation (2). The critical parameters are voltage, current, resistance, capacitance etc.

The surface produced by EDM consists of a multitude of small craters randomly distributed all over the machined phase. The C.L.A. values of surface finish ranges between 2 - 4 microns. The quality of the surface depends upon the energy of spark. If the energy content is high, deep craters will result leading to poor surface. With increase in frequency of sparking surface finish improves. The surface produced by EDM has better wear characteristics due to hardening of surface layer. But the microcracks developed reduce the fatigue strength. Tensile strength is not much affected.

The holes produced by EDM are usually tapered due to frontal spark followed by side spark. Taper at any section is found to be proportional to d^2 , where d is the diameter of tool.

Overcut in EDM is due to side spark and is dependent on gap length and crater dimension. It was experimentally shown that overcut $O = AC^{1/3} + B$, where A and B are constants. Over cut increases with capacitance.

2.4 Electrochemical discharge machining of non conducting materials:

This is a recent development in the field of machining nonconducting materials. The configuration resembles with ECAM except that the work is nonconducting. Of course the electrolyte used in this process is mainly sodium hydroxide.

The workpiece is immersed in the electrolyte and the tool electrode is mainly in contact with the workpiece. The other electrode is kept in the electrolyte. The contact area of the tool with the electrolyte is much less than that of the other electrode with the electrolyte. A suitable voltage is applied across the electrodes. Bubbles are generated at the electrode due to electrochemical action and electrical discharge may occur through the gas bubble in the event of blanketing of the electrode surface. The work piece is melted, vapourised or mechanically eroded [11, 12]. Different electrolytes and tool materials can be used in the process and wide range of non conducting materials like glass, ceramics etc. can be machined. Considering the low set up cost the process is picking up momentum and the work is in progress in I.I.T. Kanpur [13] .

CHAPTER - III

EXPERIMENTAL OBSERVATIONS AND RESULTS

3.1 Introduction:

As mentioned in section 1.1 electrochemical machining and electrodischarge machining are two major methods of machining difficult - to - machine metals and alloys. These processes have their own limitations on metal removal rate. However Electrochemical Arc machining has been found to yield higher metal removal rates.

In Electrochemical Arc Machining higher feed rates and higher voltages as compared to ECM are used. The mechanism of metal removal has been considered to be a combined effect of electrochemical dissolution and electro-discharge erosion.

In the present work the emphasis is given on investigation into metal removal rate. A number of experiments have been conducted to study the effects of voltage, feed rate and concentration on the metal removal rate. The work was confined to machining of high speed steel. Most of the tests were conducted with 'NaCl' as electrolyte. However, a few tests were also done with sodium Hydroxide solution. Attempt has been made to develop some insight into the mechanism of metal removal to explain the experimental results.

3.2 Experimental Set up

The experimental set up is shown in figure 3.1. It consists of the following elements:

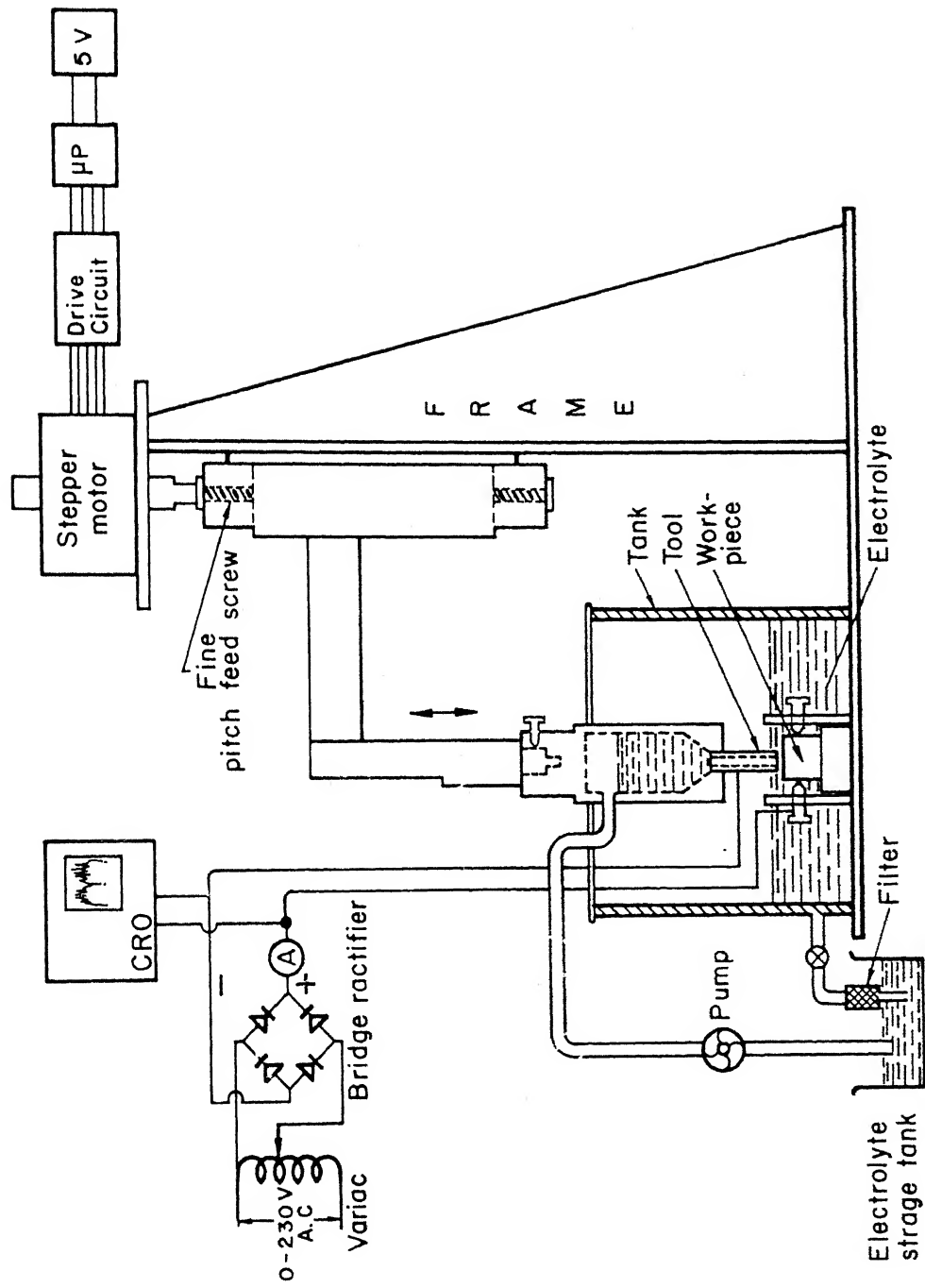


Fig. 3.1 Experimental set-up

1. D C Power Supply
2. Tool Feed System
3. Electrolyte Circulation System.

The D.C. Power Supply consists of a variac, a full wave rectifier with arrangement to measure the voltage and current and current in the circuit. An oscilloscope is connected to monitor the voltage.

The tool feed system consists of a stepper motor with a drive system. The stepper motor is connected to a feed screw arrangement which imparts motion to the tool the drive system consists of a microprocessor and a motor drive circuit (details are given in appendix A1). The microprocessor generates step command pulses, times and controls the excitation of windings. It sends signals to the drive circuit which controls the current supplied to the motor. Thus the drive system rotates the stepper motor and feed screw connected to it.

The electrolyte circulation system has got a pump, a filter and a reservoir tank. The electrolyte from the reservoir tank is pumped through the tool to the machining area to flush the gap. The electrolyte is filtered and recirculated. For the flushing purpose, hollow tools were used. The tool was connected to the tool holder which in turn was connected to the feed system. The workpiece was held inside the electrolyte tank by means of a fixture. The tool is made as

cathode and workpiece as anode as in E C M.

3.3 Experimental procedure:

Experiments were conducted with NaCl as electrolyte. However a few experiments were performed with NaOH solution. Initial tests were conducted to select feed rates and voltages appropriate to ECAM. The feed rate range selected was from 0.35 to 0.7 mm/min and the voltage range was between 30 and 45 V. The voltage wave form is in the form of a rippled D.C. In all the present work the electrolyte was circulated through the tool at a constant rate 12.5 C.C/sec. The tool selected was a 3.17 mm copper tube with a wall thickness of about 0.7mm. The smaller size tool was selected keeping in view the low current carrying capacity of the electric circuit components. At higher feed rates the process had to be terminated due to short circuit after a time of about 2 minutes. This may be due to lack of proper flushing.

The following parametric variations were studied

1. The effect of voltage and feed rate on M.R.R.
2. Effect of concentration on M.R.R.
3. Effect of voltage and feed rate on penetration rate
4. Effect of voltage and feed rate on diameter to depth ratio.
5. Zero feed rate test
6. Machining with NaOH solution
7. Reproducibility of shaped holes

Since no results were available on H.S.S., all the experiments were performed on this material. For all the experiments gap and flow rate conditions were maintained the same. The initial gap for all experiments was 0.2 mm.

The experimental results are explained below:

3.4 Experimental Results

1. Effect of voltage and feed rate on M.R.R.

First on initial gap of was set with a feeler gauge. A voltage of 30 V (r.m.s.) was applied between the tool and the workpiece. The tool was feed into the workpiece at a selected feed rate. It was found from the output of the oscilloscope that in the beginning there is not much arcing. But as the tool goes deeper and deeper the intensity of arcing increases. The current also increases. The machining was terminated after a fixed time. The work piece was taken out and the material removed was estimated by weight difference method. The experiments were repeated for different feedrates and voltages.

It was observed that for higher feed rates it was not possible to machine for a long time (especially at lower voltages) so the machining had to be stopped after some time. This may be attributed to inadequate flushing.

Fig. 3.2 shows the variation of voltage and feed rate on volumetric MRR. The MRR is found to increase with voltage and feed rate. But MRR increases with feed

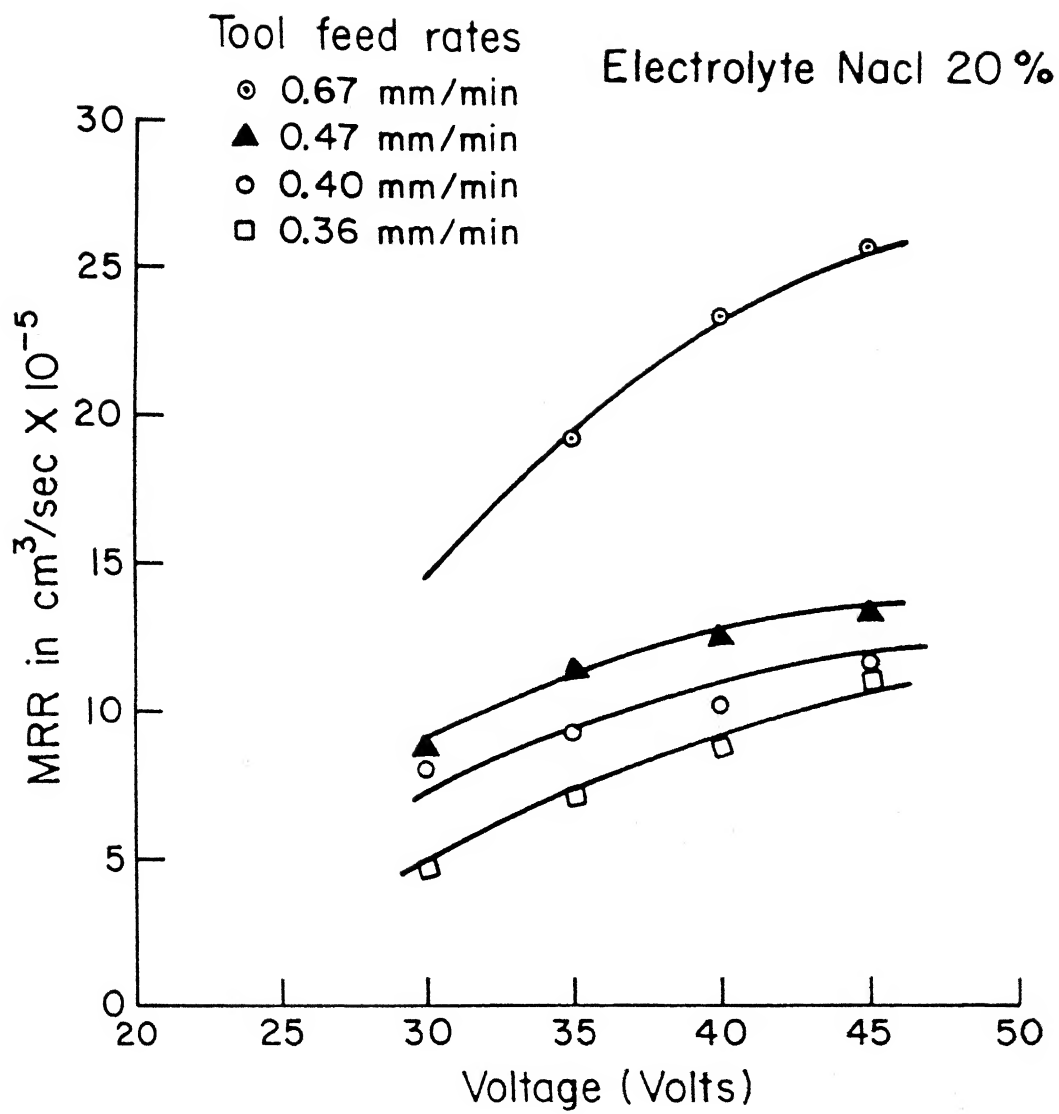


Fig.3.2 Variations of MRR with voltage at different feed rates

nation for the behaviour is explained in section 4.2

2. Effect of concentration of electrolyte on MRR:

Concentration of electrolyte is found to have some effect on M.R.R. So tests were conducted with different concentration of NaCl. Concentration of 3% , 5%, 10% and 20% solutions (Percentage weight per weight of water) were prepared. All experiments were conducted in similar conditions.

Fig. 3.3 shows the effect of concentrations on M.R.R. for different voltages. Metal removal rate is found to increase with concentration. The rate of increase of MRR is higher at lower concentration. But between 10% and 20% increases of MRR is not considerable

3. Effect of Voltage and feed rate on penetration rate:

The depth of holes drilled were measured with dial guage the movable end of which was slightly modified for the purpose. It was found that the penetration rate decreases upto about 40V beyond which penetration rate increases (Fig. 3.4). The penetration rate is found to increase with feed rate as shown in Fig. 3.5.

4. Effect of voltage and feed rate on diameter to depth ratio:

The diameter to depth ratio is a criterion frequently used to designate the accuracy of drilled holes. It gives an idea about the amount of taper in the hole.

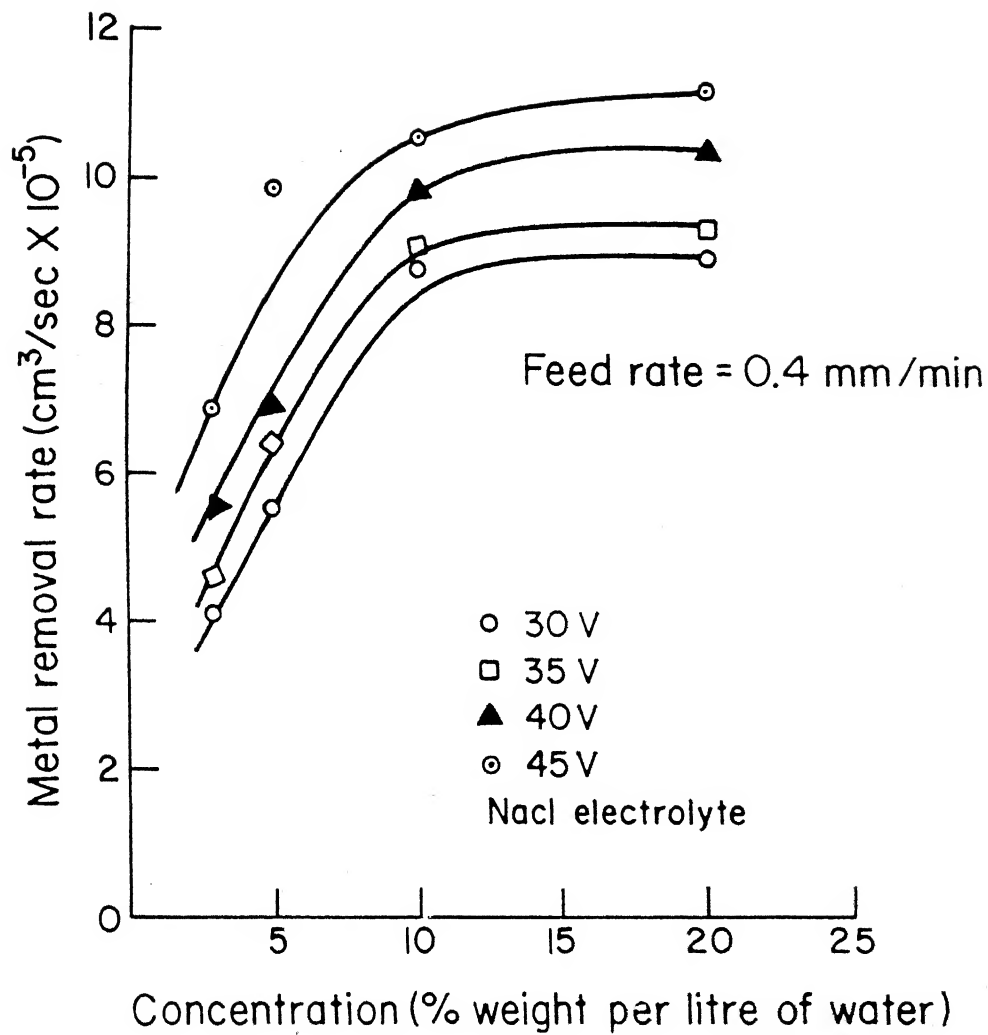


Fig.3.3 Effect of concentration on metal removal rate

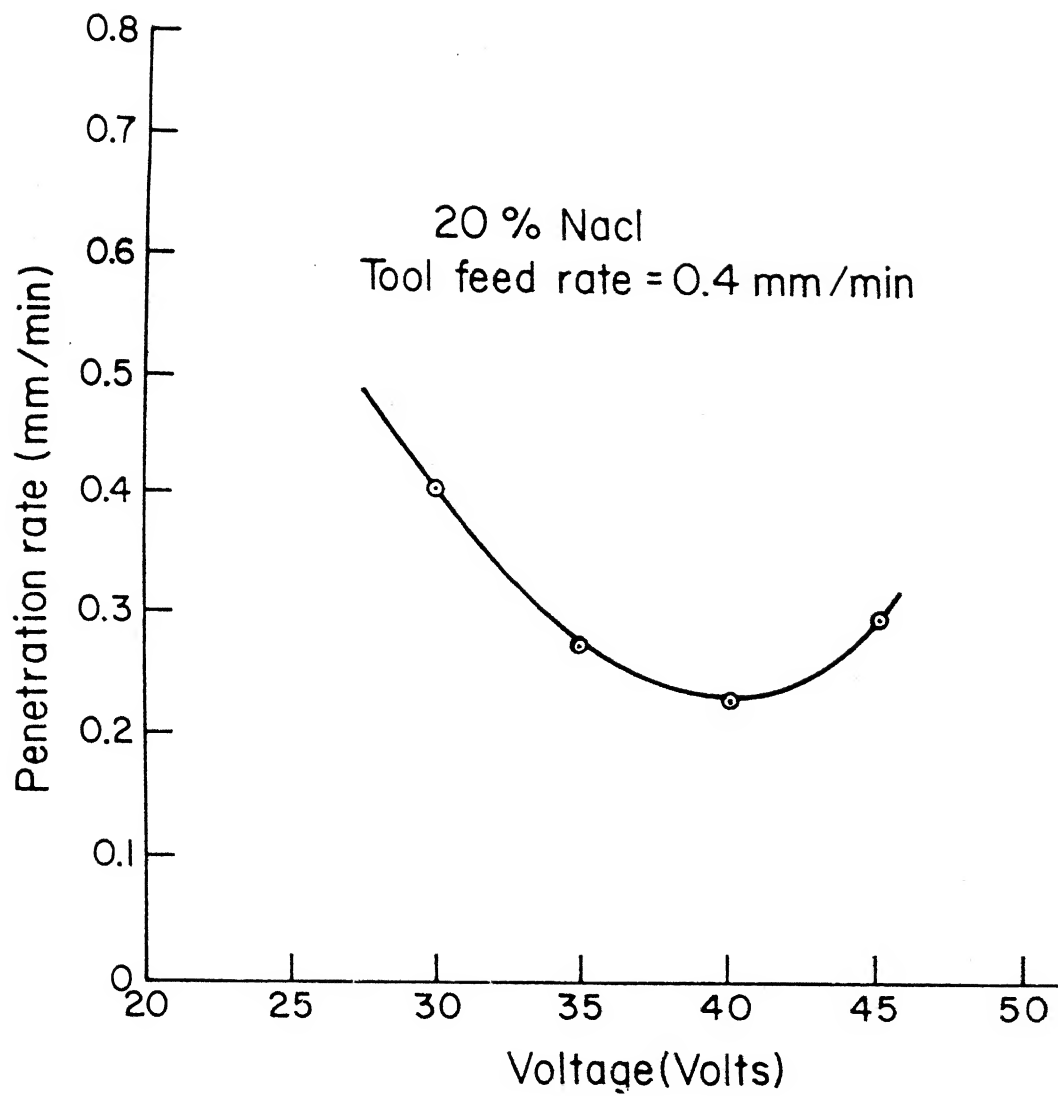


Fig.3.4 Variation of penetration rate with voltage

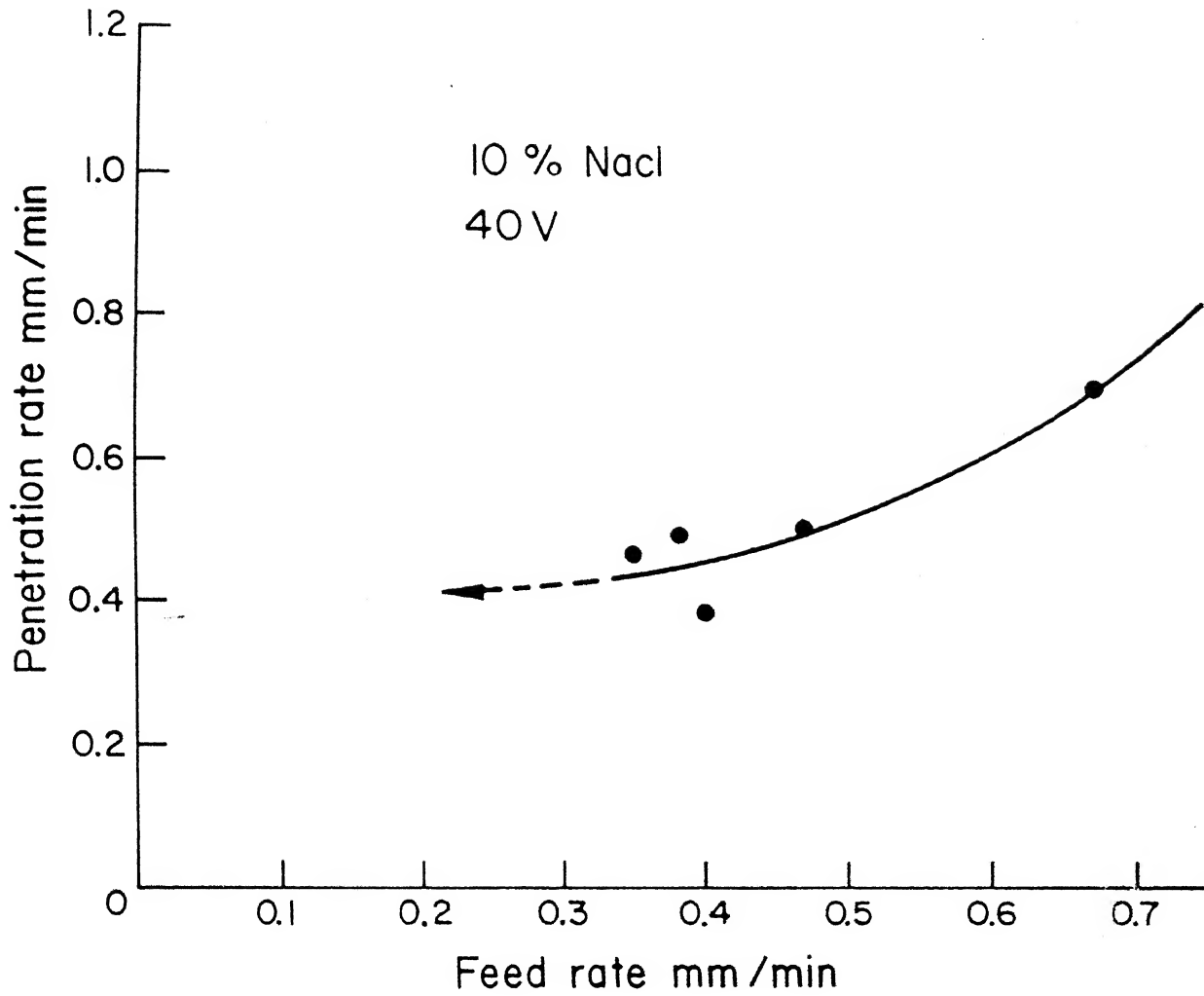


Fig.3.5 Effect of feed rate on penetration rate

Fig. 3.6 and Fig. 3.7 show the variation of the diameter to depth ratio with feed rate and voltage. The ratio of outer diameter to depth increases with feed rate. This is in conformity with the result obtained by McGeough that amount of taper increases with feed rate (Fig.1.3). The diameter to depths ratio is found to increase with increase in feed rate initially but is found to decrease at higher voltages. McGeough et al had observed that the amount of taper increases with increase in voltage (Fig.1.4)

5. Zero Feed rate test:

This test was conducted to study the effect of progressively increasing interelectrode gap on M.R.R. An initial gap of 0.2 mm was set for all tests and machining was done without giving any tool feed. After a time of 2 minutes the amount of metal removed was measured by weight difference method and the metal removal rate was calculated. The experiments were repeated for different periods of time and the metal removal rate was calculated for each time as shown in table 1. The experiment was repeated for different voltage, concentrations etc Fig. 3.8 shows the variation of the machining rate with time. The machining rate was calculated on the basis of total time. It was found that machining rate gradually decreases with time. The table 1 shows the variation of incremental MRR with time. The MRR shows an unprecedented tendency to increase after a long time

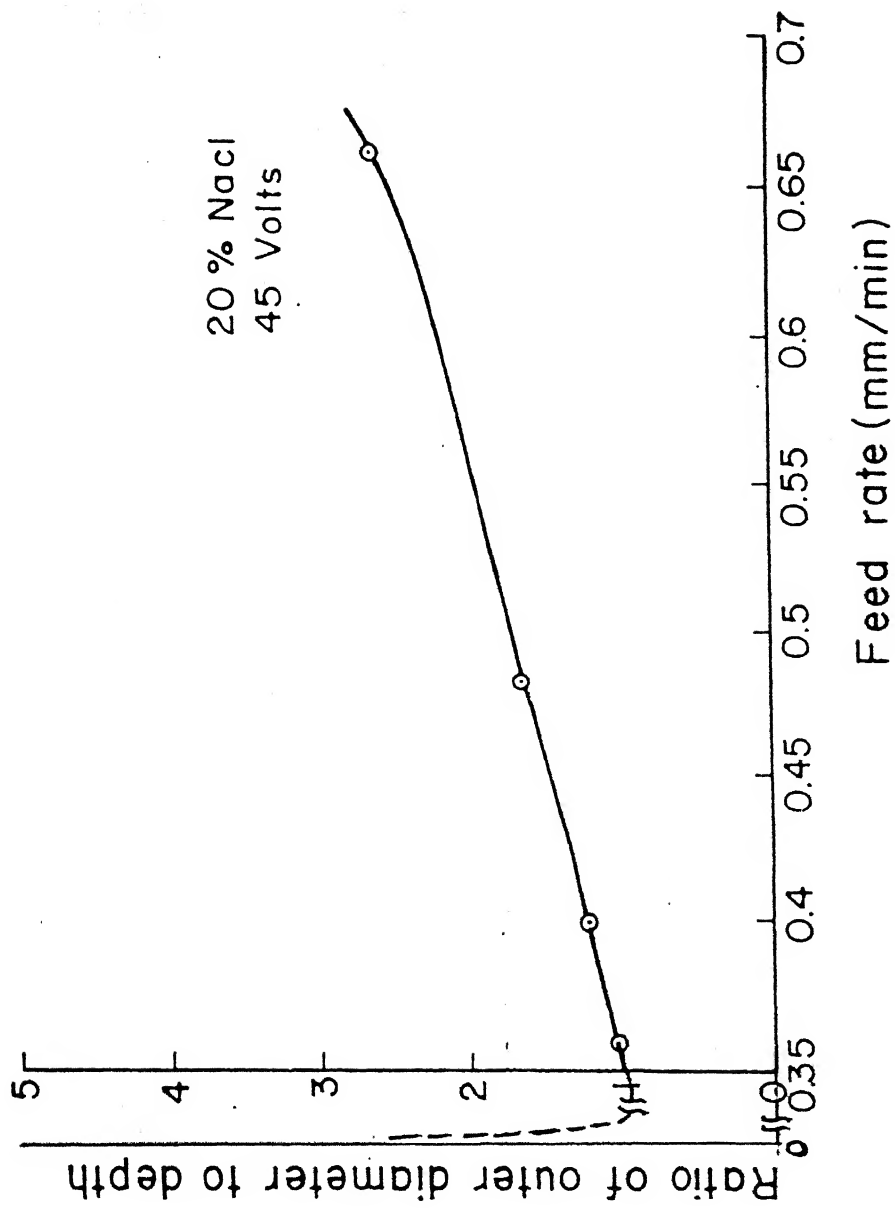


Fig.3.6 Variation of diameter to depth ratio with feed rate

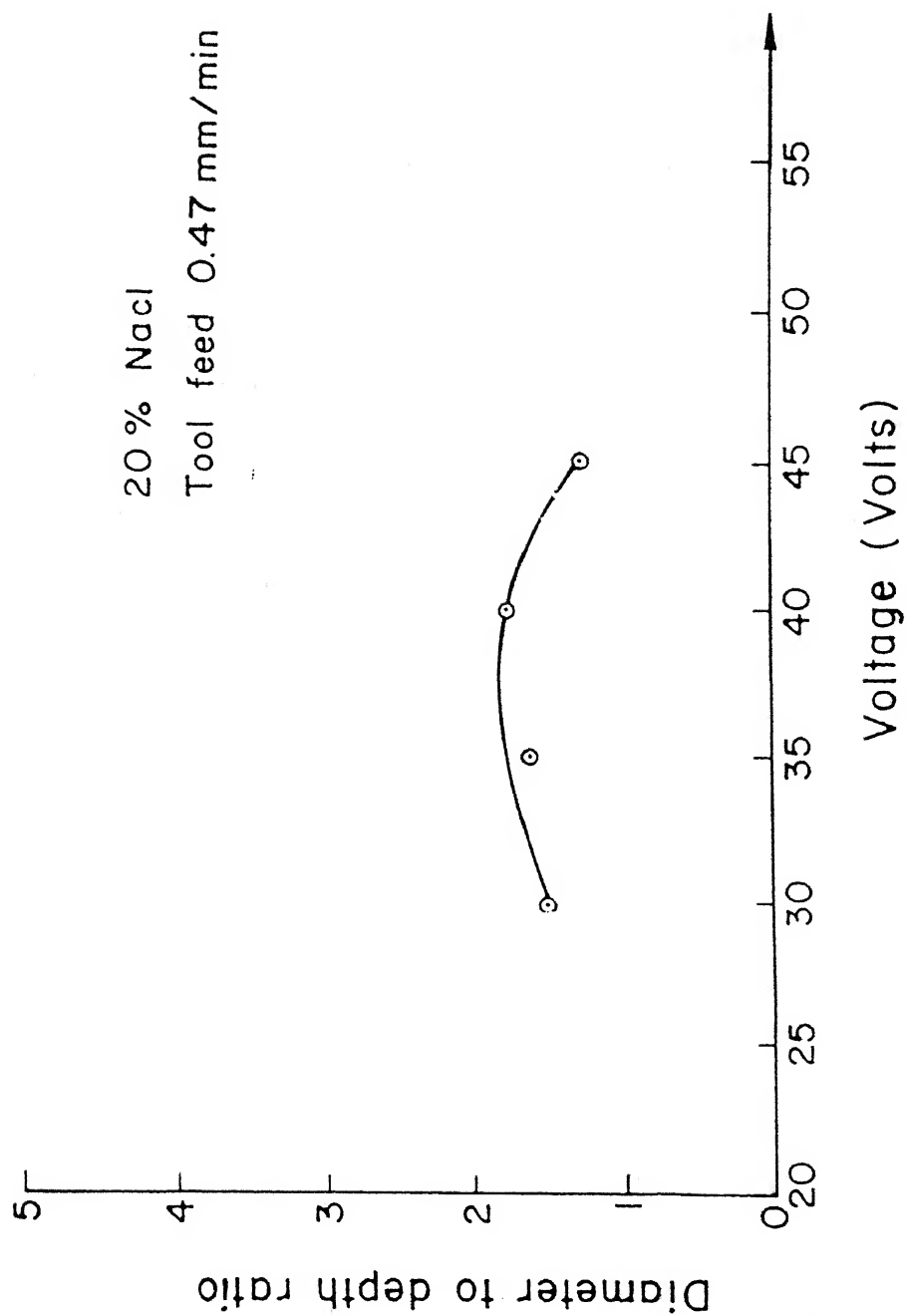


Fig 3.7 Variation of diameter to depth ratio with voltage

CONDI TIONS	time (min)	Volume of metal removed average (cm^3) $\times 10^3$	Volume of metal removed in inter- vals of Time (cm^3) $\times 10^{-3}$	Metal removed rate (average) $\text{cm}^3/\text{sec} \times 10^{-5}$	Metal removal rate in intervals $\text{cm}^3/\text{sec} \times 10^{-5}$
45V	2	7.44	7.44	6.2	6.2
5%	4	12.96	5.2	5.4	4.33
	6	16.56	3.6	4.6	3.0
	12	27.36	10.8	3.8	3.0
45V	2	6.36	6.36	5.3	5.3
	4	11.52	5.16	4.8	4.3
5%	6	12.96	1.44	3.6	1.2
	11	22.54	9.58	3.4	2.9

TABLE - 1

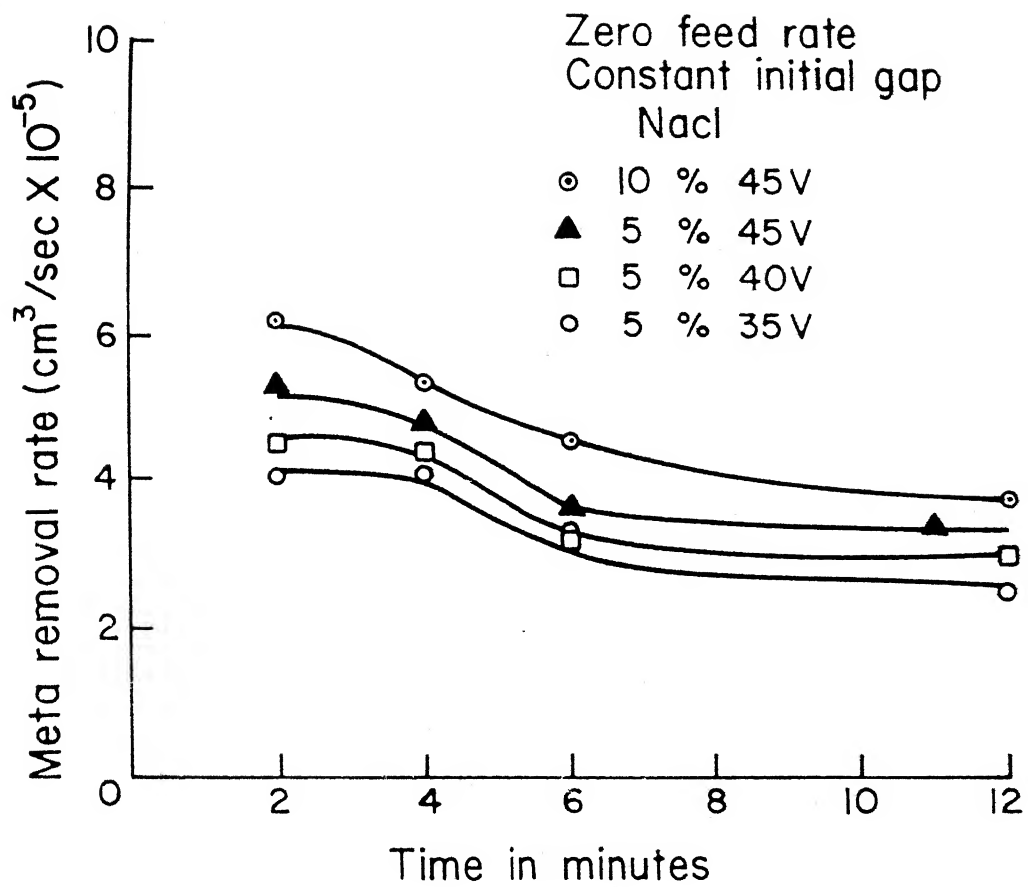


Fig.3.8 MRR vs time

as shown in the table . This may be due to some experimental error.

6. Machining with NaOH Solution:

Fig. 3.9 shows the conductivity of different electrolytes for different concentration. It is clear that the conductivity of NaOH is much higher than the conductivity of NaCl except at higher concentration. So it was expected that the metal removal rate will be very high. Some tests were conducted with NaOH solution and the machining rate was found very low. Later it was found from literature that in the case of ECM with NaOH solution the metal removal rate is negligibly small [14]. This case is true here also since ECM has a predominant effect in ECAM.

7. Reproducibility of shaped holes:

Some tools were made to drill square holes in H.S.S. blades. Corner reproduction was found difficult to get with the process. In lower voltage range the corner reproduction accuracy was found comparatively better. Some drilled holes are shown in the photographs. It may be noted that in EDM a very good corner accuracy is obtained.

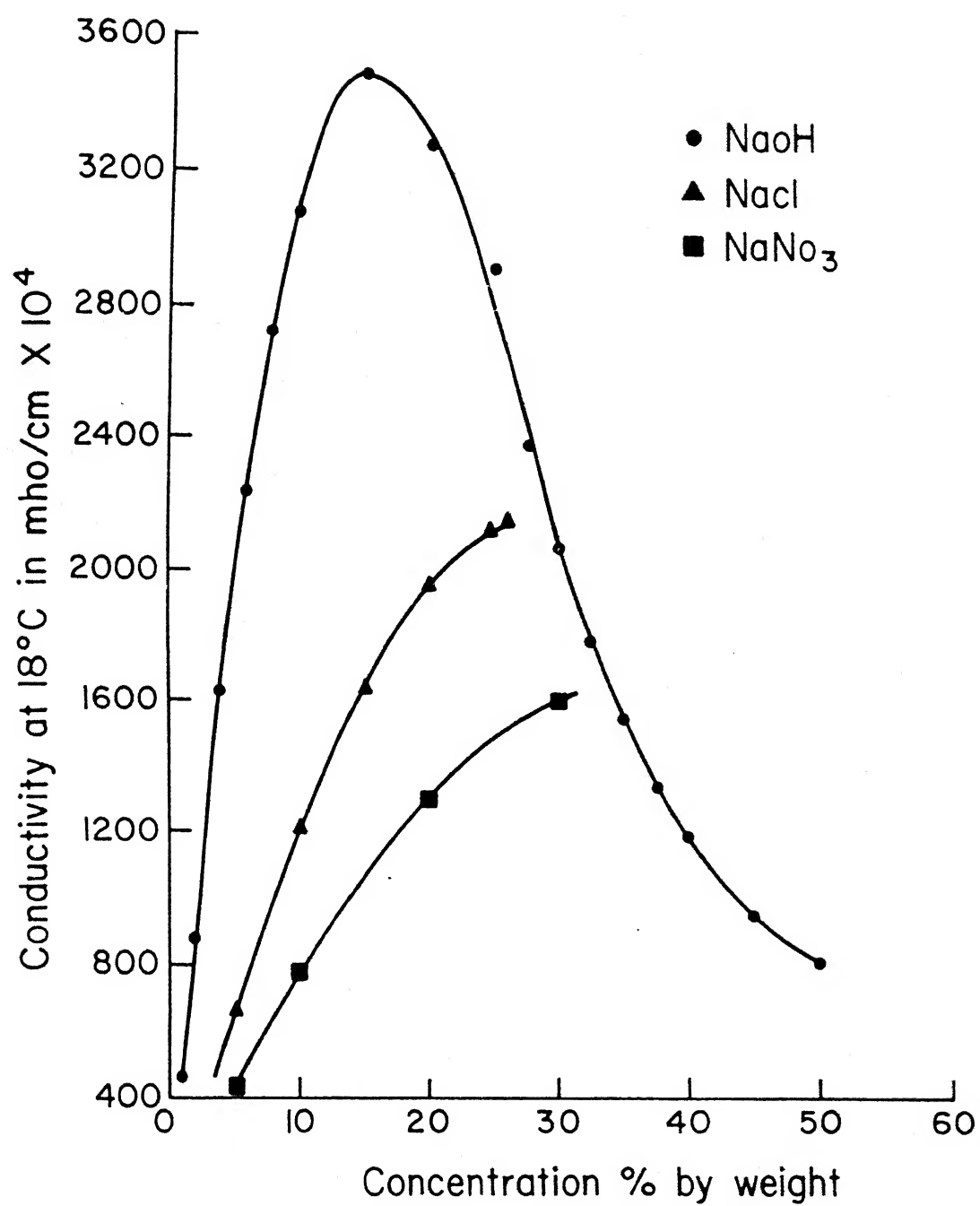


Fig.3.9 Variation of conductivity with concentration

CHAPTER - IV

DISCUSSION ON EXPERIMENTAL RESULTS

4.1 Mechanism of metal removal:

The mechanism of metal removal is not well understood so far. It has been proposed that the process is a combined effect of electrochemical dissolution and electro-discharge erosion. The discharges in the form of arcs produce craters on the work surface and the discharge erosion is assisted by electrochemical dissolution.

However it is felt that besides these, some other effects are taking place as discussed below:

1. Arcing by itself cannot remove metal in a satisfactory manner. In EDM the sparks melt and evaporate the metal on the microasperities and a small portion of the molten metal is thrown out by shock waves, pinching effect etc. Arcing is a longer duration of spark and it melts the metal. But the degree and frequency of shock waves acting on the molten metal is lesser.

2. The metal removal by discharge erosion is low compared to ECM. Now if the ECM phase is partly replaced by discharge erosion phase the metal removal rate will be between ECM and EDM rate. But this is not the case and in ECAM the observed MRR is much above ECM rate.

The above reasonings suggest a possible mechanism based on the following points:

E C A M takes place at a higher feed rate and higher voltage. At higher voltages it is observed that the probability of short circuiting is less and the chances of breaking the bridge contacts (blowing) is more. Bridge is the short lived metallic contact between two electrodes [15]. At lower voltages and higher feed rates there is a problem of short circuiting (as encountered in ECM). At high voltage and low feed rate the MRR is found to be low. And at higher voltages and higher feed rates, the MRR is observed to be very high.

Based on the above points, the mechanism can be explained as follows. The contributing models for the metal removal may be

1. high rate electrochemical dissolution.
2. Micro asperity bridge contacts and blowing of bridges due to electrical pressure
3. Oxygen environment coupled with metal at kindling temperature leading to oxidations of metal
4. Removal of some molten metal by high velocity electrolyte flow.

These are explained below

1. Higher feed rate and Higher voltages leads to high current density due to which metal is dissolved at faster rate.

2. The blowing of bridge-contacts can be explained as follows. When two high tension wires are touched, instantaneously there will be blowing of metal. At higher feed rates there are more chances of micro asperity contacts and blowing of metals. The temperature at the contact becomes very high due to which there will be expansion of gases and generation of shock waves which helps in metal removal. It is a known fact that perfect metal to metal contact is not possible and there is always a very thin insulating layer of the order of angstroms or microns. In many cases the insulating layer is an oxide layer. This insulating layer acts as a barrier. So in the case of asperity contacts due to this thin layer, high field effect is developed and field emission occurs. This causes an avalanche of electrons which strikes on the surface raising it to a very high temperature. Metal is melted and vapourised and also there will be a sudden expansion of gases which removes the metal.
3. The asperity contacts mentioned above raises the metal to its kindling temperature. At the anode oxygen is produced and in the oxygen environment the metal is oxidised away.
4. If the flow velocity is sufficiently high some molten can be removed by the flowing electrolyte.

4.2 Discussion on Experimental results:

1. Effect of Voltage and Feedrate on MRR.

From Fig. 3.2 it is clear that feed rate has more influence on MRR than voltage. Fig.4.1 illustrates this point more clearly. At higher feed rates the gap is lesser, current density is higher and so the rate of anodic dissolution is more. Also at higher feed rate the microasperity contacts are more due to which more metal is melted and subsequently removed. But with increase in voltage, the rate of bridge contact is lesser as compared to the increase in feed rate. This is because the gap becomes more due to more ECM action. So metal removal rate is not high. With higher feed rates and higher voltages metal removal is found to be very high.

2. Effect of Concentration as MRR

As shown in figure 3.3, at lower concentration region, rate of increase of MRR is large while between 10% and 20% the increase of MRR is not considerable. It is reported that the extent of stray cutting in ECM is found to increase with NaCl concentration increasing from 13.5% to 20% [17]. The increase in stray cutting at higher concentrations can be explained by referring to Fig. 4.2. At lower concentrations there are lesser number of ions for carrying the current and most of the ions will be concentrated in the cutting region and stray cutting is less

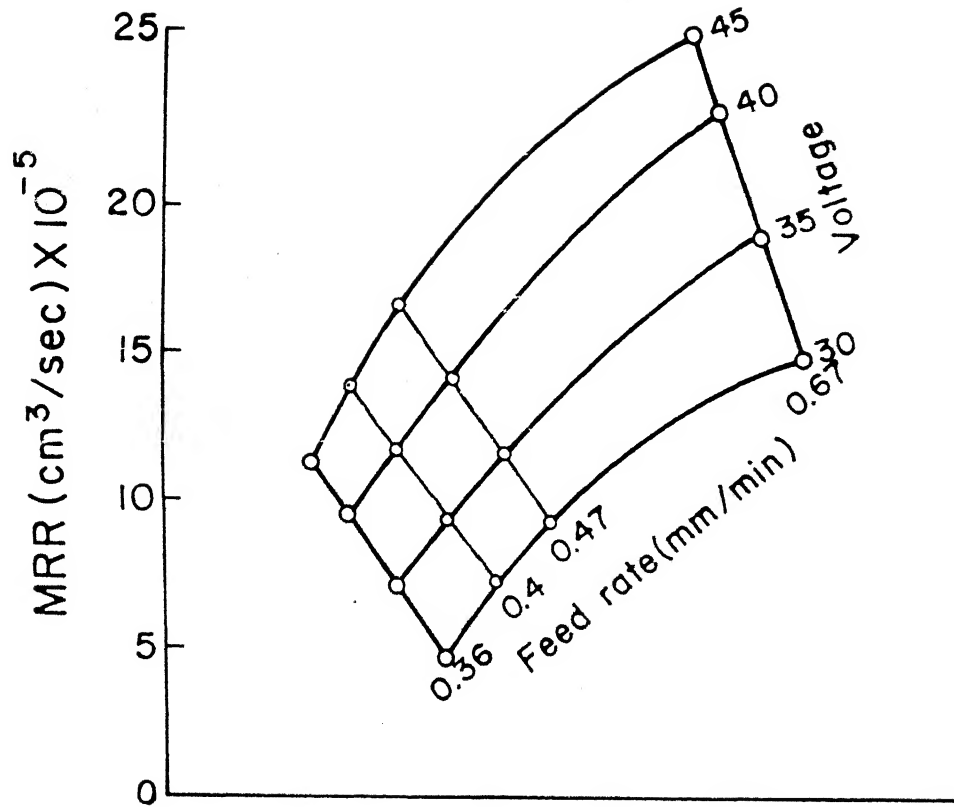


Fig. 4.1 Illustration of the influence of feed rate and voltage on MRR

But at higher concentration there are large number of ions for carrying the current. So current will be carried to the sides also by the presence of ions and extent of stray cutting will be more as shown in the figure. This stray cutting will reduce the current efficiency and the metal removal rate will be lesser than expected. Since ECM has a predominant role in ECAM, the overall contributions will be less. That is the reason why there is not much increase in metal removal rate between 10% and 20%

3. Effect of voltage and feed rate on Penetration rate:

The penetration rate is found to increase with feed rate. At higher feed rates intensity of arcing is more. There is high rate dissolution as well as more asperity contacts which throw off the metal from the contact so the penetration rate is more.

With increase in voltage, the penetration is found to decrease. This result is in conformity with the result obtained by McGeough et al (Fig. 1.8). With increase in voltage the rate of bridge contacts will decrease. So the penetration rate decrease. Instead more side cutting occurs. However, after about 40 volts penetration rate is found to increase. The probable reason is that upto 40 v passivation may occur and after 40 v the passive stage is converted into transpassive stage [17]. So current efficiency increases and the penetration rate also increases.

McGeough's result (Fig. 1.8) shows that tool wear rate can be as high as 100% of penetration rate. This explains the possibility of drilling holes where penetration rate is less than the feed rate. In our case tool wear is not monitored.

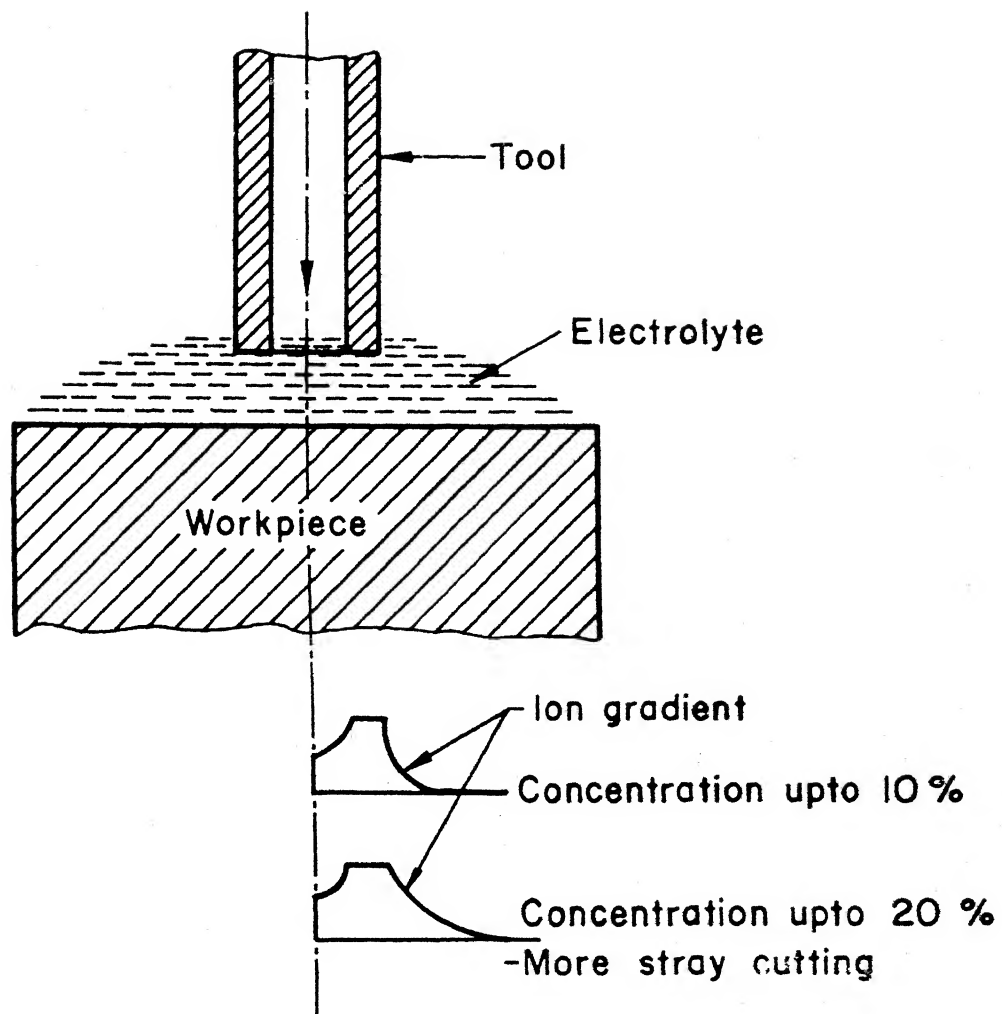


Fig. 4.2 Illustration of stray cutting at higher concentration of 'NaCl'

(4) Effect of Voltage and feed rate on diameter to depth ratio.

The diameter to depth ratio was found to increase with feed rate as shown in Fig. 3.6. In ECM with increase in feed rate there is less time for dissolution and it is expected that the taper would decrease. But in the case of ECAM the metal removal is mainly due to blowing of bridges with increase in feed rate the frequency of bridge blowing increases and also the energy content increases. So more area is affected thereby diameter increases. So the diameter to depth ratio increases with feed rate.

With increase in voltage also the diameter to depth ratio increases. With increase in voltage the energy of blowing increases. So the diameter increases and hence the diameter to depth ratio increases. But after a voltage of 40 V (Fig. 3.7) the diameter to depth ratio decreases. It was observed that in ECM current efficiency increases with anode potential to a certain value, then decreases and then increases. This is due to passivation and transpassivation [17]. This may be the probable reason for the stray cutting between 30 V and 40 V. After 40 V the current efficiency may increase because the passive film dissolves and breaks. So diameter to depth ratio decreases.

5. Zero feed rate test

From the Zero feed rate graph (Fig. 3.8), an approximate value of MRR for 10% NaCl and 40 V condition found to be $6 \text{ cm}^3/\text{sec} \times 10^{-5}$.

Since tool diameter is 3.17 mm,

$$\begin{aligned} \text{Corrospending linear feed rate} &= \frac{6 \times 10^{-5} \times 10^3 \times 60}{\pi \times \frac{3.17^2}{4}} \\ &= 4.56 \text{ mm/min} \end{aligned}$$

It can be seen that if the figure 4.5 is extrapolated to zero feedrate condition the penetration rate of approximately 4 mm/min obtained. This is in agreement with the penetration value at the beginning of the zero feed rate graph.

As the time elapses in the zero feed rate test, the process tends to be moving towards electrochemical machining condition. Subsequently the process decays with stray cutting.

6. Machining with NaOH solution:

With NaOH as solution the machining rate was found to be very low or negligible. Similar results were obtained in ECM previously [4] and it is also reported that for most metals and alloys, NaOH is not a suitable electrolyte due to the formation of adherent insoluble anodic products which further prevent or restrict the dissolution

of the work piece [16] . This is also the case with ECAM. This shows that ECM plays a major role.

4.3 Comparision with ECM

The metal removal rate in ECAM is found to be 2 to 3 times higher than ECM rate at higher feed rates. Fig. 4.3 shows a comparision between theoretical ECM and experimental ECAM rates. The specific metal removal rate in ECAM is found to be higher than the specific metal removal rate in ECM. The calculation of specific metal removal rate in ECM is shown in Appendix A2. The specific metal removal rate is much higher especially at higher feed rates and voltages. This is an important feature of the process and it shows that for the same amount of energy, ECAM has got much higher metal removal than ECM process.

4.4 Conclusion and future scope of work

Conclusions:

1. The process can be advantageously used in rough machining of difficult to machine metals and alloys. However, finishing cut may be given by EDM or ECM
2. Metal removal is found to be 2 to 3 times that of ECM. The metal removal rate has been found to be a strong function of feed rate. Concentration of electrolyte and applied voltage influences MRR to a lesser degree than feed rate.

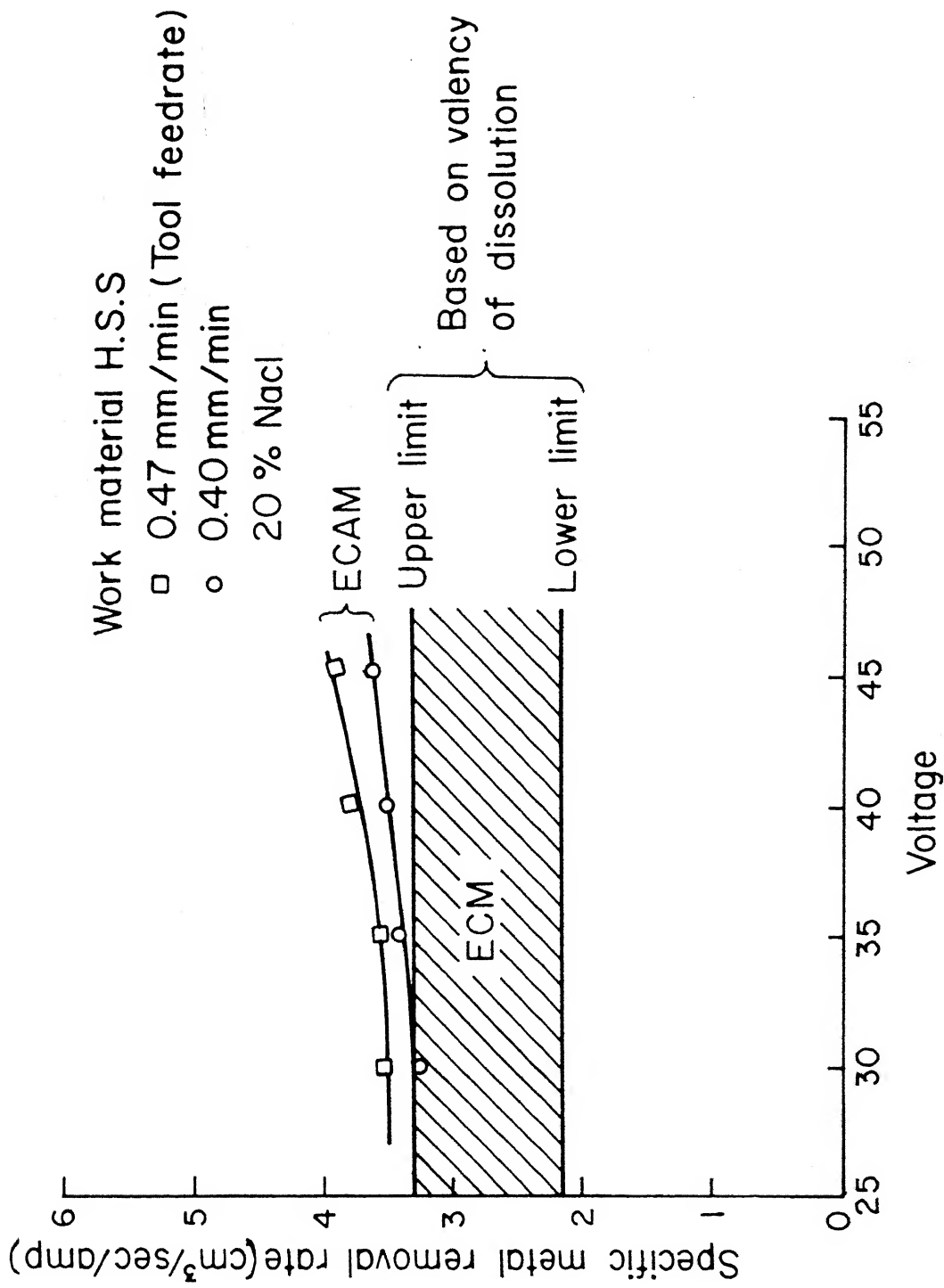


Fig.4.3 Comparison between ECM and ECAM

3. ECAM process is realised at higher feed rates and higher voltages as compared to normal ECM. To obtain higher MRR higher feed rates and voltages should be used.
4. Penetration rate decreases with voltage upto about 40 V and then increases

Future Scope of Work:

1. Further investigation into machining of difficult materials like Titanium, Tungsten Carbide, hard alloys etc.
2. Since metal is removed possibly by blowing of micro contact bridges, a debris analysis may be conducted to throw more light on the mechanism of metal removal.
3. A mathematical modelling of the process is required to compute MRR and study the effects of different parameters.
4. The flow system should be improved to obtain higher MRR. The electrolyte should be pumped at a higher pressure.
5. Since the process very much depends on the formation of short circuit bridges leading to arcing, radio signal detection method explained in section 1.3 can be used successfully to study the nature of arcs/sparks, its energy, frequency etc. to give more insight into the mechanism of metal removal and to enhance the potential of the process.

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APPENDIX - A 1

Details of Stepper Motor

Make : Automatic Electric Co. Bombay.
Angle/Step : 1.8°
No. of Steps/rev. : 200
Voltage : 12 V D.C
Current : 1.5 Amp/phase
Torque : 3 kg cm

Details of Microprocessor Kit

Make : Professional Electronic Products, Meerut.
Model : 8085 based (8 bit)

Drive Circuit : Standard circuit fabricated in the lab.

A P P E N D I X - A 2

For an alloy, the metal removal per unit charge is given by the following equation

$$U = \frac{100}{\rho_m F} \frac{1}{\frac{X_1 Z_1}{A_1} + \frac{X_2 Z_2}{A_2} + \frac{X_3 Z_3}{A_3} + \dots} \text{Cm}^3 \text{A}^{-1} \text{S}^{-1}$$

Where $X_1, X_2, X_3 \dots$ = Weight % of each element

$Z_1, Z_2, Z_3 \dots$ = Valency of dissolution of each element

$A_1, A_2, A_3 \dots$ = Atomic weights of each element.

ρ_m = Density of alloy in gm/cm^3 .

The following table gives the weights percentages, atomic weights, valencies of dissolution and the densities of each element in H.S.S.

	Co	W	V	Cr	Fe	C
Weight %	10	18	1	4	66.25	0.75
Valencies of dissolution	2, 3	6, 8	3, 5	2, 3, 6	2, 3	-
Density (g Cm^{-3})	8.85	19.35	6.14	7.19	7.86	-
Atomic weights (g)	58.93	183.85	50.95	51.99	55.85	-

$$\begin{aligned} \text{They density of alloy} &= \frac{100}{\frac{18}{19.3} + \frac{4}{7.19} + \frac{1}{6.14} + \frac{66.25}{7.86} + \frac{10}{8.85}} \\ &= 8.92 \text{ g cm}^{-3}. \end{aligned}$$

Taking the lowest valencies of dissolution and substituting in the above equations, the highest specific metal removal rate that is possible is $3.3079 \times 10^{-5} \text{ cm}^3/\text{sec/amp.}$

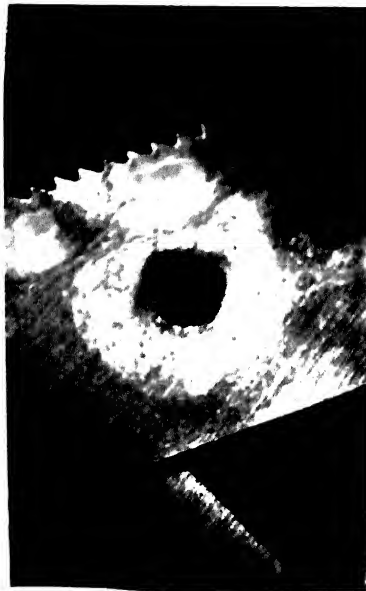
Taking the highest valencies of dissolution of each element and substituting in the equation the lowest specific metal removal rate that is possible is $2.1471 \times 10^{-5} \text{ cm}^3/\text{sec/amp.}$



Tool used



30 V



35 V



40 V



45 V



EDM 40 - 45 V, 1A